EVALUATION OF THE UTILITY OF SEDIMENT DATA IN NASQAN
(National Stream Quality Accounting Network)

by

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Report to:
U.S. Geological Survey
Contract No. 14-08-0001-17541

Memorandum No. 23

June 1983

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ABSTRACT

Monthly suspended sediment discharge measurements, made by the USGS as part of the National Stream Quality Accounting Network (NASQAN), are analysed to assess the adequacy in terms of spatial coverage, temporal sampling frequency, accuracy of measurements, as well as in determining the sediment yield in the nation's rivers.

It is concluded that the spatial distribution of NASQAN stations is reasonable but necessarily judgemental. The temporal variations of sediment data contain much higher frequencies than monthly. Sampling error is found to be minor when compared with other causes of data scatter which can be substantial. The usefulness of the monthly measurements of sediment transport is enhanced when combined with the daily measurements of water discharge. Increasing the sampling frequency moderately would not materially improve the accuracy of sediment yield determinations.

CHAPTER 1

INTRODUCTION

The purpose of this study was to evaluate the usefulness of the sedimentation data in the National Stream Quality Accounting Network (NASQAN). NASQAN encompasses a wide variety of water quality parameters, including measurements of suspended sediment concentration, which is the only component we are considering in this report. The overall objectives of NASQAN are: (1) to define the present conditions of water quality throughout the United States, and (2) to identify changes or trends that are taking place in natural water quality, due to both natural and human factors. The fully-implemented NASQAN program includes 525 stations distributed in all hydrologic regions in a way which samples 90 percent of the nation's surface water, except along the seacoasts, where many small streams discharge into the ocean. For a more detailed description of the NASQAN network, its purposes, data analysis and evaluation, see reports by Briggs and Ficke (1979) and Controller General (1981).

This study is directed toward answering the following critical questions regarding the sediment data in NASQAN:

(1) With the present NASQAN system (sampling for the concentration of suspended sediment monthly at a network of 525 fixed stations), what specific sedimentation questions can be answered in relation to primary NASQAN objectives (including the computation of

annual sediment loads and peak concentrations and loads)?

(2) What improvement might be made in the sampling network, measurements, and frequency of measurements that would improve the data base in terms of its ability to satisfy NASQAN objectives?

Among the issues being considered are:

(1) Spatial network of field measurement stations.

(2) Sampling frequency.

(3) Types of measurements needed.

(4) Measurement procedures.

(5) USGS analyses and publication of data.

Recommendations for further research will also be presented.

CHAPTER 2

BASIC USES FOR RIVER SEDIMENTATION DATA

There are several types of information which are needed in order for us to understand and manage the sediment problems in the nation's rivers. These information needs are enumerated below without regard to whether they can be answered with just NASQAN data or whether more detailed sedimentation data are necessary. However, they will provide the frame of reference for the discussion of utility of NASQAN data in the following chapters. The topics are presented below in approximate order from headwaters to coastlines.

(1) Rate of Erosion of Hills and Mountains. Over the long term the weathering and erosion of mountains and hills are the basic sources of sediments to stream systems. We describe the erosional denudation rate in terms of depth per year averaged over the surface areas. For example, in the San Gabriel Mountains in southern California the average denudation rate is approximately 1 millimeter per year (or 1 meter per thousand years). Although the basic weathering can be considered a fairly uniform process, the removal of weathering products by rainfall and runoff can be extremely variable. For example, in southern California storms on a burned watershed may remove over 40 millimeters in one winter.

The typical method of determination of the denudation rate is to observe the accumulation of sediment in a catch basin, which is immediately downstream of the erosional areas, without significant valley depositional areas upstream of the catch basin. For example, a debris basin to trap sediment at the mouth of a canyon would satisfy this requirement.

Not only is the rate of erosion important, but also we must know the distribution of grain sizes in the eroded material over the full range of sizes -- boulders, gravel, sand, silt and clay. The reason we must know this distribution is to understand or predict the subsequent downstream deposition pattern of the material which is eroded. For example, the very coarsest material (boulders and gravel) will only be moved in the largest flood flows and will be deposited on the heads of the alluvial fans. Sands will move much larger distances and be the principal component of the deposits in the major river valleys; however, there is significant through-put of the finest sands to the shoreline. The silts and clays are predominantly transported as washload, i.e., they basically flush through the stream system without much deposition or interaction with the bed sediments. However, during floods when there are large overbank flows, then significant amounts of silt along with some sands and clays deposit in the overbank areas, causing the flood-plains to aggrade.

(2) Rate of Soil Loss from Valley Areas (including developed agricultural and urban land). The long-range fertility of agricultural land depends upon the prevention of the loss of soil by rainfall and runoff. Control by various soil conservation measures focuses on the eroding land surface as the principal damage may be to the areas of loss rather than to downstream areas where the sediments

may be deposited.

The loss of soil may occur by surficial processes and gullying; or such loss may occur by bank erosion along streams that transect valley floors. Meandering streams in particular (when not stabilized) may cut out huge swaths of previously deposited sediments along with the overlying topsoil.

As in the case of mountain erosion the distribution of grain sizes in the eroded material is of very great importance in determining the subsequent deposition of the eroded material.

(3) Rates of Stream Channel Erosion and Deposition; River Training and Stability. In the natural state, river channels in alluvial valleys will periodically shift within their channel locations, either through moving meanders or by shifting braided channels. Vertical aggradation and degradation also occur depending upon the balances of water and sediment flows.

Man's occupancy of the flood plain, often in major urban centers along river channels, requires that the rivers be trained or stabilized to maintain a fixed course. While in some areas like Los Angeles the streams are completely lined with concrete and the coarser sediments are excluded from the channels by upstream dams, the more usual situation is a stream which is semi-controlled, i.e., still behaving partly as a natural stream while engineers try to maintain an alignment with levees, revetments, drop structures, and other training works. An essential feature of all of these man-made works to control natural rivers is that the modified river must still be capable of transporting the sediment discharge which enters any given reach, without either scour or deposition. A major imbalance can be absolutely disastrous; for example, a severe shortage of sand during a flood may cause a river to severely degrade or scour the bed, often undermining bridge piers or the toe rock of revetments, leading to failure of levees at much less than supposed design flows. On the other hand, if a stabilized river channel receives sediments greatly in excess of equilibrium transport rates, the stream channels will aggrade sometimes to the point of actually filling completely and spilling flood waters into the surrounding areas. A very dramatic example of that was the Cowlitz River in the state of Washington following the Mount St. Helens eruption in May 1980.

(4) Rate of Sedimentation in Reservoirs. In the planning for any water storage reservoir, a critical concern is the amount of sediment which will be trapped in the reservoir over a period of time, leading to the gradual loss of useful storage. However, the impact of reservoir sedimentation is also felt far downstream from major dams because of the starvation of the stream for sediment load, which may lead to serious degradation, bank caving, and other difficulties with the stream channel (e.g., the Nile River below Aswan Dam).

In a few places, such as flood control dams in southern California, the sedimentation rate is so severe (and sometimes intentional) that the sediments must be removed from reservoirs at periods of the order of every 20 to 30 years in order to maintain the reservoir function.

(5) Assessment of Sediment Hazards Associated with Floods. As the foregoing discussion indicates, the behavior of sediments can cause severe hazards and damage to man and man's activities. These range from landslides and mudflows in upland areas to rapid deposition on alluvial fans, to inundation by flood waters caused by either excessive or deficient sediment as explained under item 3 above. Structural damage to bridges, pipeline crossings and other river structures may also occur due to undermining or burial. The assessment of these sediment hazards is an important part of the national flood insurance program, both for setting proper rates for insurance as well as keeping developments out of areas which are too hazardous.

(6) Patterns of Estuarine and Lagoonal Deposition. River sediments do not always get all the way to the ocean because they become trapped in estuaries and lagoons, particularly in shoreline areas which are generally subsiding relative to sea level. In particular, fine sediments (clays) flocculate in estuaries when they come in contact with brackish or salt water and often settle rapidly. This deposition may be of such significance as to require extensive dredging in order to maintain navigation (e.g., the Hudson and Delaware River estuaries; San Francisco Bay/Sacramento River Delta; James River/Chesapeake Bay). Sands and silts are also deposited in estuaries because of the reduced water velocities even though they may not be subject to flocculation.

Lagoons are also sediment traps because of the low water velocity and the salt water intrusion.

Overall, sedimentation in estuaries and lagoons may not only severely impact the use of these bodies of water, but also stops the delivery of sand sizes needed for beach replenishment.

(7) Rate of Delivery of Sediment to the Shoreline. In the long run, the beaches shift back and forth in response to fluctuations of riverine import of sand and the action of waves and littoral currents. For man's use of the beaches, we sometimes try to maintain them with much less fluctuation than that which would occur naturally, e.g., through the use of various protective measures such as groins, jetties, and breakwaters. However, on a broad scale, man is making large perturbations in the sand delivery to the shoreline in two ways: (i) the change of the river flow regime (modified flood peaks or total flow reduced by diversions); (ii) reduction of the amount of sediment flow due to dams, debris basins, and river channel stabilization. The long-range management of shorelines depends on adequate information on the sources of sediment as well as the losses offshore during storms and by littoral drift into canyons.

A recent study by Brownlie and Taylor (1981) gives an example of the assessment of the impact of man-made works in decreasing the sediment delivery by streams to the southern California shoreline below what naturally would have occurred without the works.

(8) Water Quality in Relation to Beneficial Uses. Surface water is used for a great many water supplies (urban, industrial and agricultural), and for many in-stream uses (fisheries, recreation).

The sedimentation effects on water quality primarily come from the finer sediments, silt and clay, rather than the sand sizes. At water intakes, sand is sometimes withdrawn along with the water, but this is easily removed by proper sedimentation tanks or redesign of the flow geometry of the intake works. More serious water quality problems occur because of the very fine material which causes turbidity and because the large specific surface of small particles may be the carriers of trace contaminants.

For water supply (municipal and industrial), turbidity must be removed by water treatment through the use of proper flocculating agents. For agricultural use turbidity may be beneficial in increasing soil fertility or may be detrimental in possibly sealing the land (i.e., reducing permeability).

These water quality problems may be traced to the sources of sediments as described in items 1 and 2 above. Once the wash load (silts, clays and colloidal material) enters the system most of it is transported through the system, except through very large reservoirs. The waters, of course, are more turbid during flood events when the erosion of the land is accelerated.

* * *

In general it is clear that the information needs for the above topics are very site specific and depend on many details of the sequence of hydrologic events, such as floods. This means that it is difficult to aggregate information and make general integrated assessments with respect to trends in sedimentation data. In other words, the fluctuations are so great from place-to-place and at a given place from time-to-time that we may consider it a very noisy signal from which we are trying to find a gradual trend.

The concept of sediment yield is worthy of special attention here. It is defined as the average rate of river outflow of sediments from a given watershed, either as a total quantity per year or as an average depth per year over the watershed. If the watershed includes depositional areas in valleys as well as hill and mountain areas, then the sediment yield is <u>not</u> equivalent to the denudation rate. The reason for this is that much of the erosion from the upland areas may be deposited in the immediately adjacent valley areas and thus may not be delivered to the measuring station for the whole watershed, which may include the valley areas. This is why there is a tendency for the sediment yield expressed as a depth per year to decrease as watersheds get larger. The interpretation then of sediment yield for large river basins is extremely tricky because it may reflect the combination of many counter-balancing factors. For example, the lack of a trend on the Mississippi River may obscure two counteracting trends, such as increased soil loss from the Great Plains being balanced by decreased bank erosion due to channel stabilization. It is clear that the untangling of multiple effects cannot be simply done by measuring stream transport rate or sediment yield at downstream stations on large river basins. However, this is the principal type of sediment information included in NASQAN.

In the following chapters we will explain what kinds of analyses can be done and explain to what degree the questions enumerated in this chapter can be addressed with this data.

CHAPTER 3

CHARACTERISTICS OF THE TIME SERIES FOR SELECTED RIVERS

A. Introduction

In this chapter the sediment transport data is examined as time series for selected river systems. Six river systems were chosen for study from the entire NASQAN station network. These cover a variety of locations around the nation and also exhibit varying characteristics. First, spatial variations are treated, then several of the stations on these river basins are further analyzed in terms of their temporal variations.

It will be seen that the nature of the sediment data as time series exhibit variations possessing a very broad range of time scales from the very long to the very short. A particular station on the Upper Mississippi was examined in detail and showed significant temporal fluctuations with a time scale of only a few days. Regular monthly NASQAN (spot) measurements of sediment concentration therefore do not, in general, characterize the time series, and cannot be utilized to deduce temporal variations reliably on their own. Since NASQAN includes continuous measurements of water discharge on all of its stations, and since sediment concentration and water discharge are correlated (although to varying degrees), any analysis of sediment transport would benefit from consideration of the daily water discharge information along with the monthly sediment measurements.

B. Selection of River Basins for Analysis

On a smaller scale, such as an individual river basin, the choice of the spatial distribution of stations would be expected to be influenced by local considerations. In an attempt to examine the sub-regional characteristics of station location and density, six representative, intermediate-sized river systems were chosen. These river systems are identified in Table 3.1. In the choice of these particular systems, an attempt has been made to include a range of geographic locations and hydrologic characteristics. These six river systems will also form the basis of analysis for other features of the NASQAN sampling strategy to be discussed later. It is simply beyond the scope of this investigation to examine data from each station.

In Figures 3.1-3.6, the river systems are diagrammed, identifying the NASQAN station locations, their respective drainage areas, long-term mean discharges (over 30-90 years) and average annual runoff. It is interesting to examine the distribution of new discharge monitored by each additional station as one moves downstream along with the flow. Table 3.2 tabulates mean discharge values for NASQAN stations included on each river system and identifies incremental discharge values for higher-order stations (downstream from other NASQAN stations). For NASQAN stations in each of the six river basins, mean discharge values for both primary tributary stations and incremental discharge values for higher-order stations (Table 3.2) vary considerably.

TABLE 3.1

River Basin Characteristics

River Basin (States)	Drainage Area (km^2)	Number of NASQAN Stations on River
Susquehanna (Penn/ Md)	1×10^5	5
Mobile (Ala)	2×10^5	5
Upper Mississippi (Minn/Wis/Iowa)	2×10^5	9
Brazos (Tex)	1.5×10^5	6
Snake (Ida/Ore/Wash)	3×10^5	8
Gila (Az/NM)	1.5×10^5	9

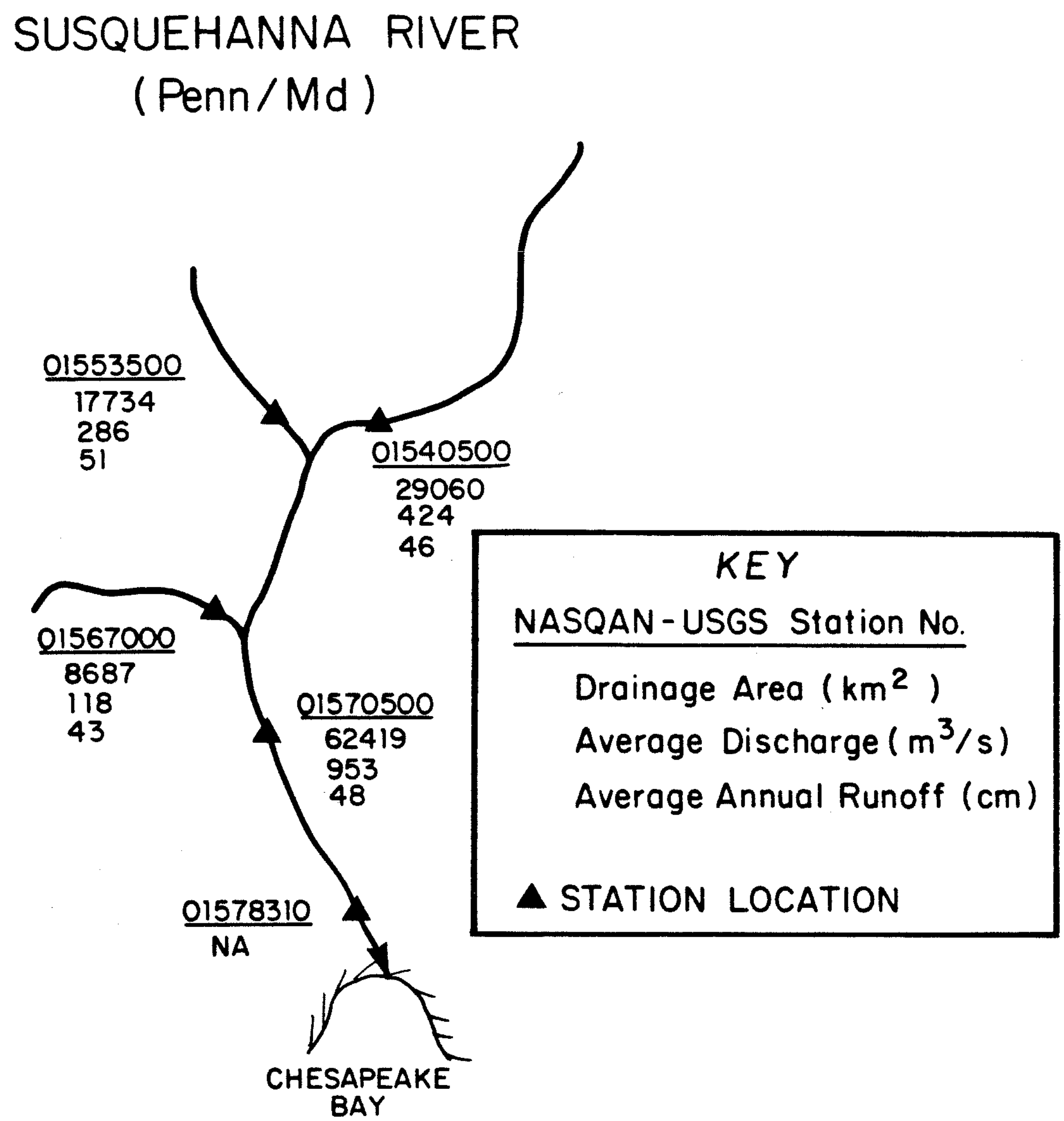


Figure 3.1 NASQAN station locations on the Susquehanna River.

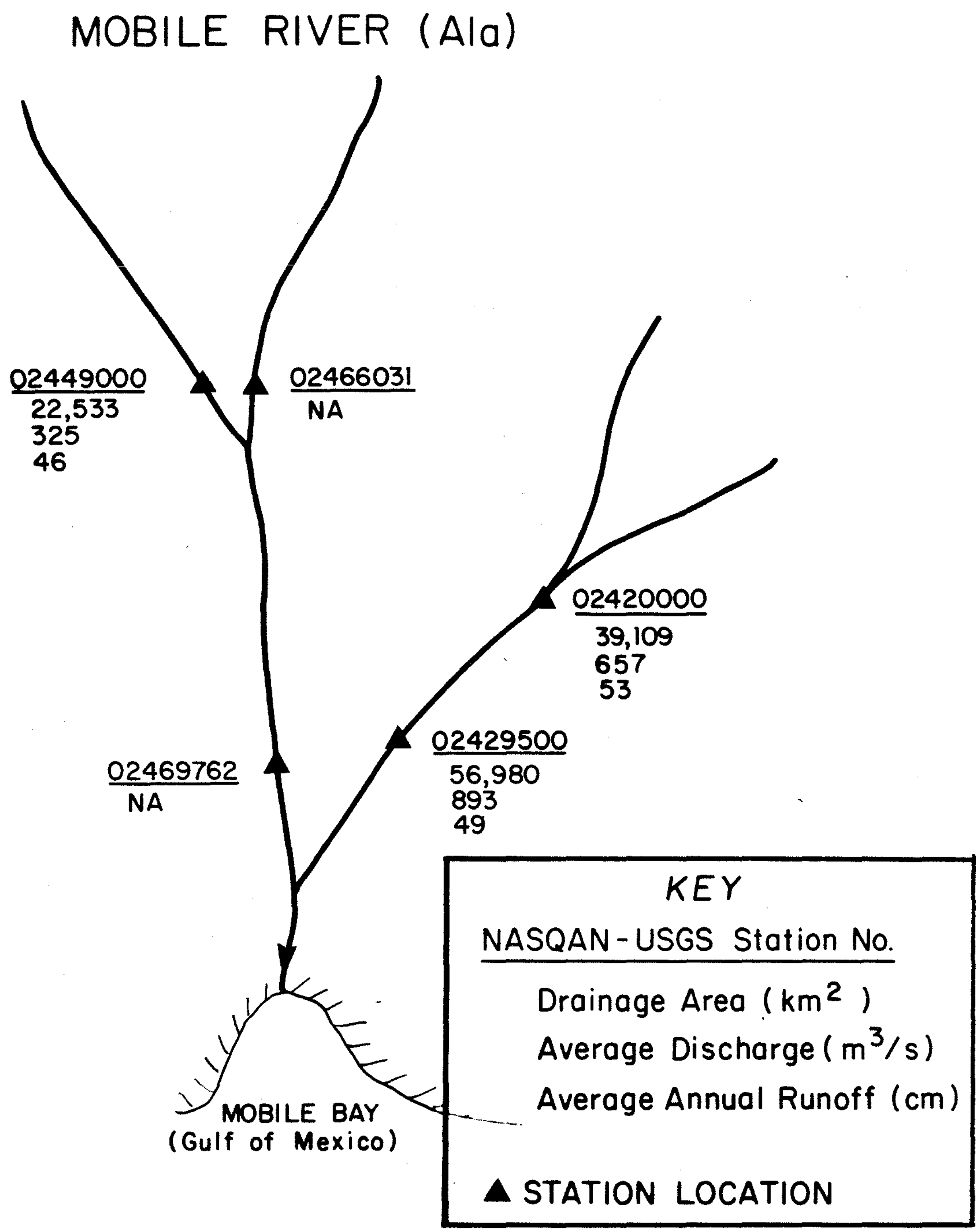


Figure 3.2 NASQAN station locations on the Mobile River.

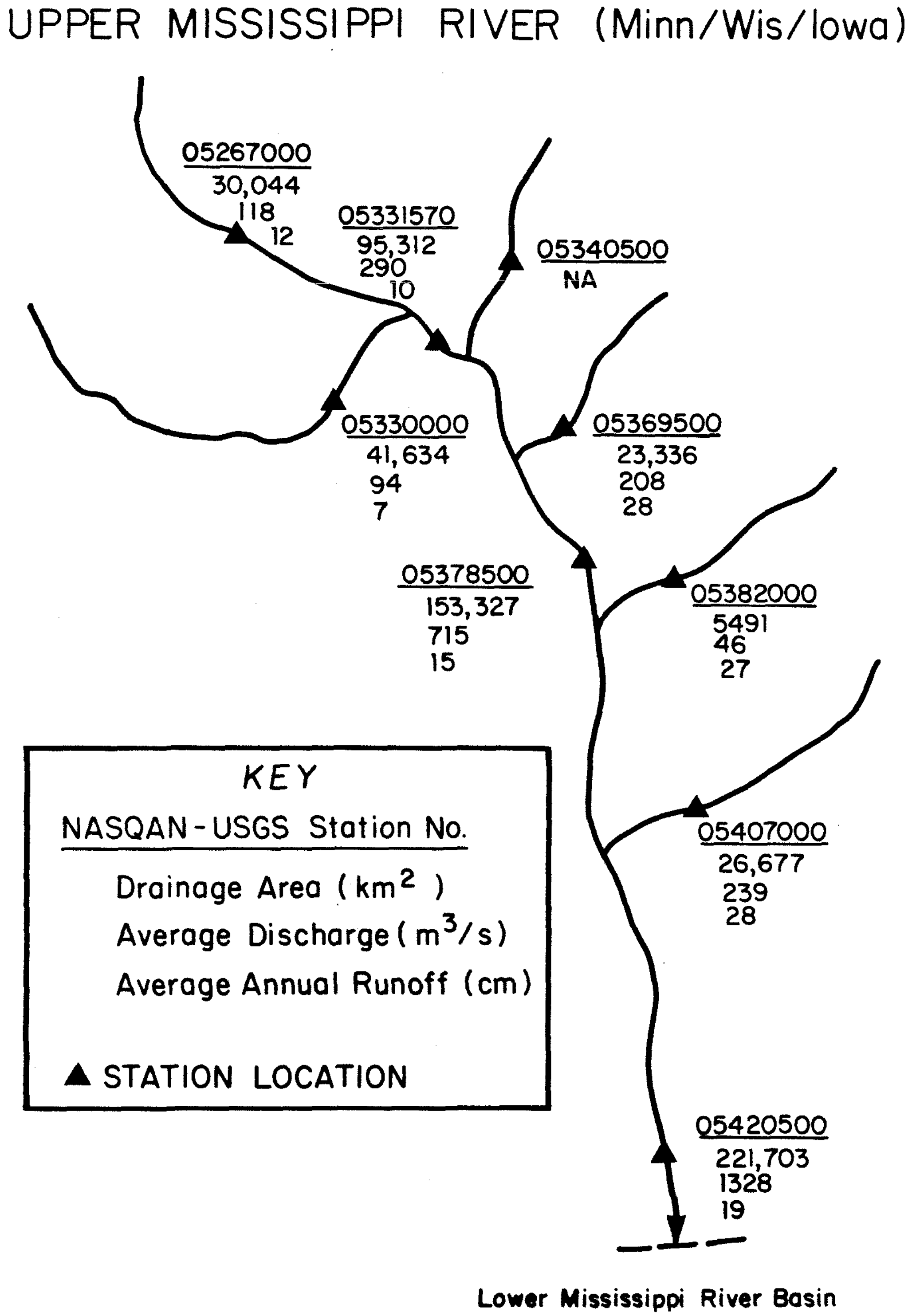


Figure 3.3 NASQAN station locations on the Upper Mississippi River.

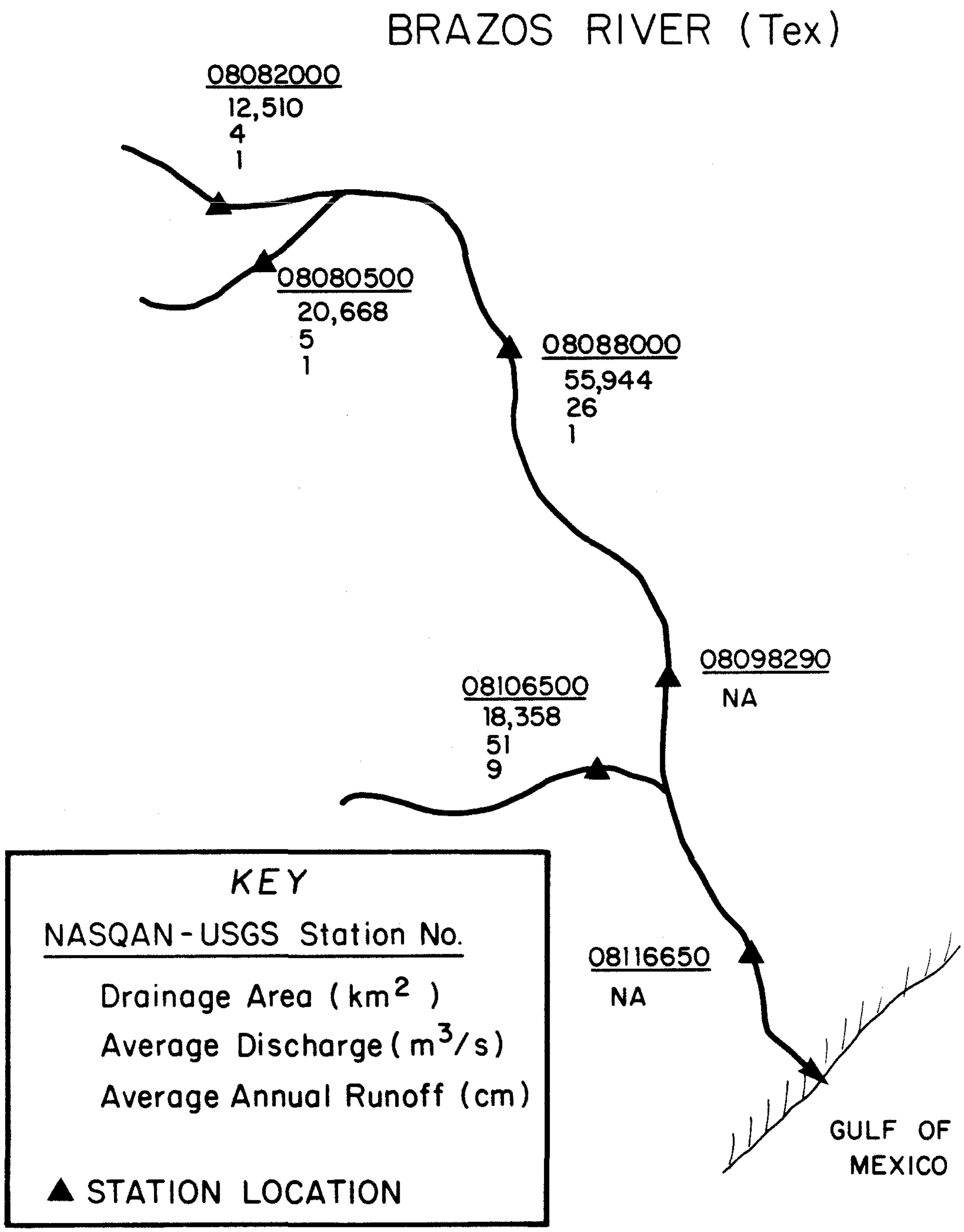


Figure 3.4 NASQAN station locations on the Brazos River.

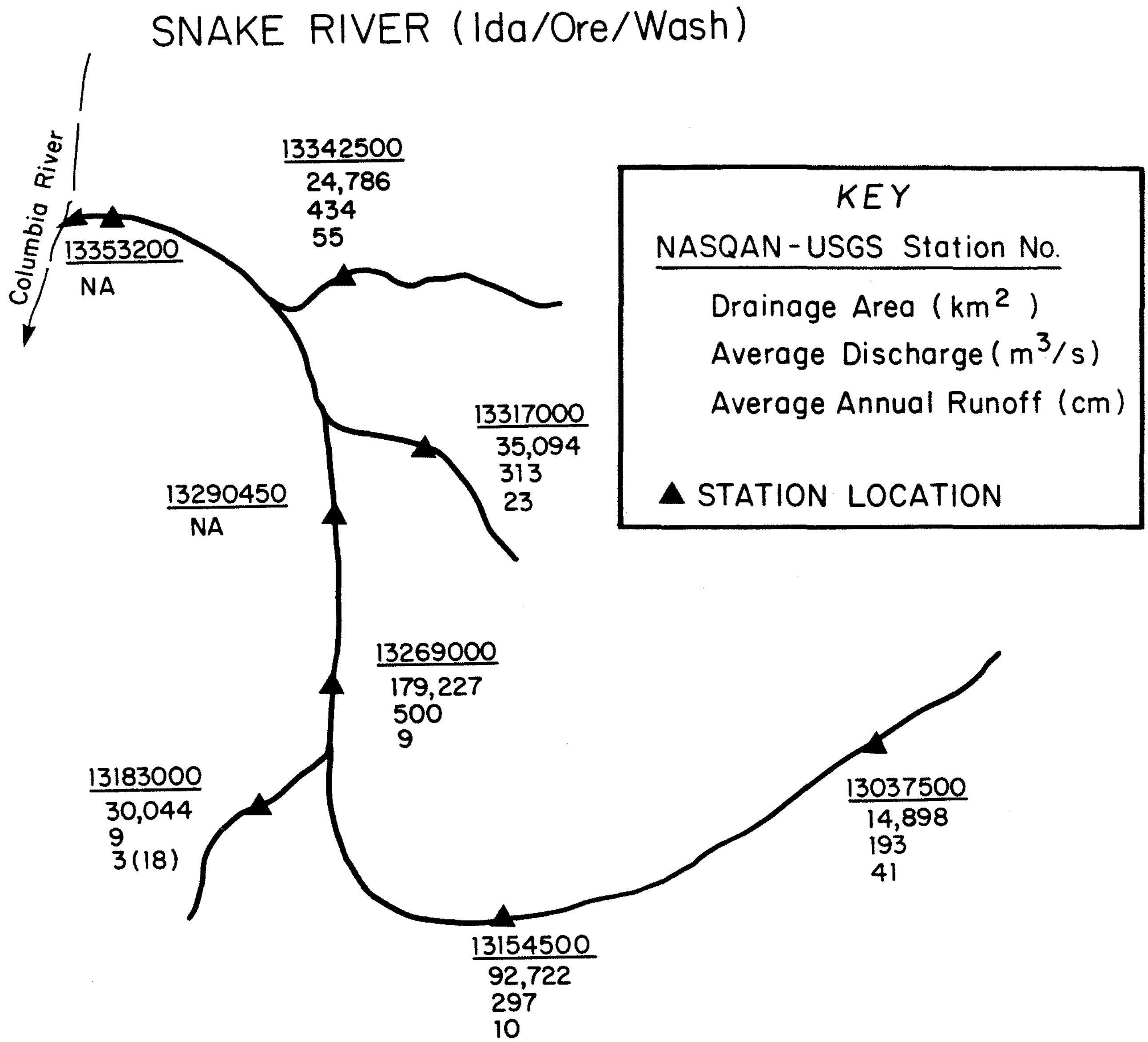


Figure 3.5 NASQAN station locations on the Snake River.

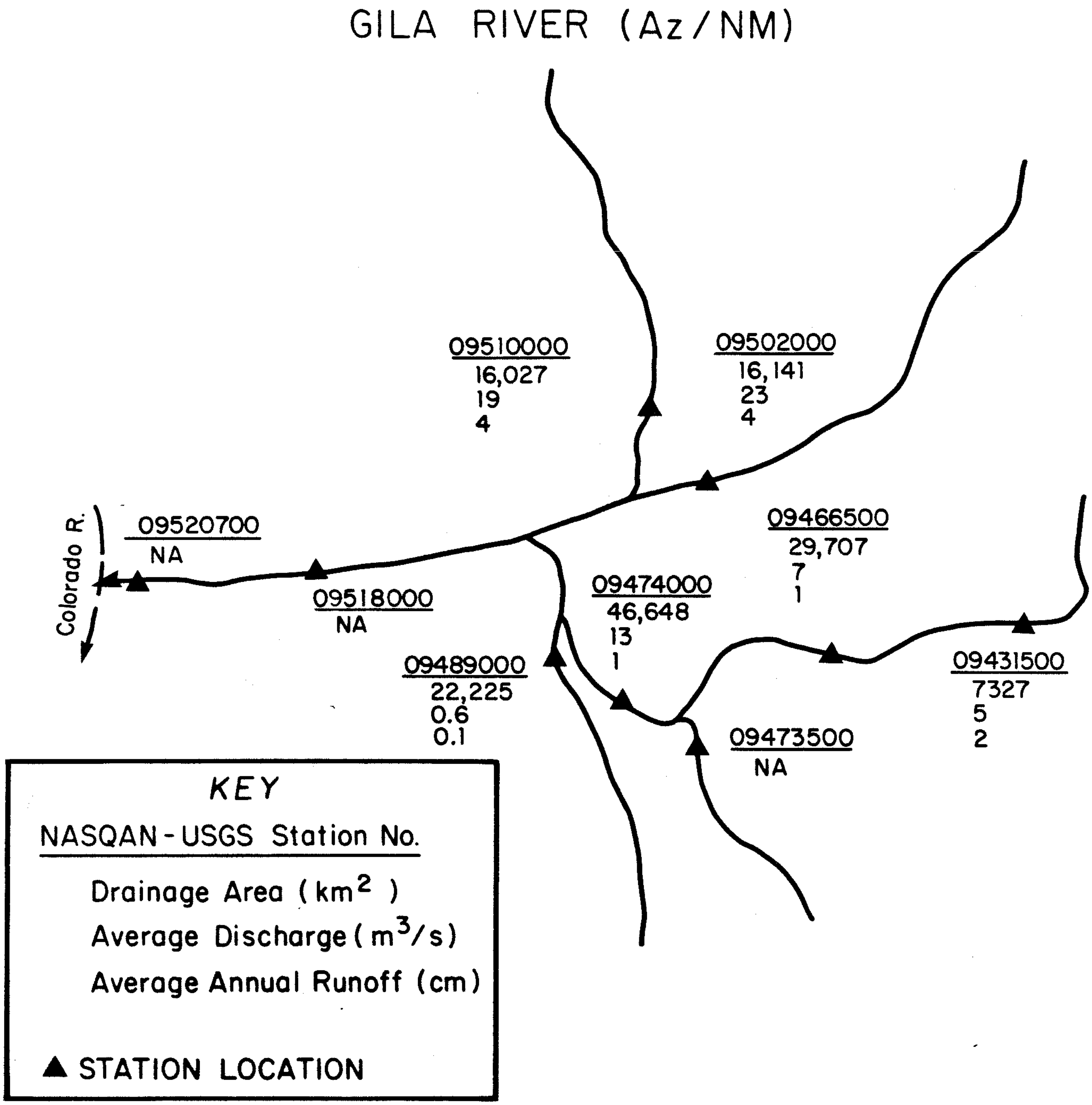


Figure 3.6 NASQAN station locations on the Gila River.

TABLE 3.2

30-90 Year Mean Discharges* (m^3/s)
at NASQAN Stations on 6 River Systems

River System	Primary tributaries	Higher order tributaries		
		Note: Quantities in Parentheses designate incremental discharge below upstream stations		
Susquehanna River (Penn./Md)	286			
	424			
	118	953(125)	NA**	
Mobile River	325			
	NA	NA		
	657	893(236)		
Upper Mississippi River above Davenport, Iowa (Minn/Wis/Iowa)	94			
	118	290(78)		
	NA			
	208		715(NA)	
	46			
	239			1328(328)
Brazos River (Tex)	4			
	5	26(17)		
	51			
	NA		NA	
Snake River (Ida/Ore/Wash)	193	297(104)		
	9		500(194)	NA
	313			
	434			NA
Gila River (Az/NM)	5	7(2)		
	NA		13(NA)	
	0.6			
	19			
	23			

*Discharges given in cubic meters per second (USGS, WSP:2101-2137)

**Insufficient data at this station (or upstream stations) to determine this discharge (or incremental discharge).

The inter-basin variation in mean discharge (both primary tributary and incremental values) is much larger, ranging from 0.6 m^3/s in the Gila to 424 m^3/s on the Susquehanna for a variation of nearly 3 orders of magnitude, and these stations are not "outliers."

It should be noted that three of the six river systems include stations below dams. There are two on the Mobile, one on the Snake and three on the Gila.

In Figures 3.1-3.6, the mean runoff values for the drainage areas above the NASQAN stations are given where available data would allow their computation. On the Susquehanna, there is little variation in these runoff values, and the mean for the basin lies between 45-50 cm. This is also the case on the Mobile River. On the Upper Mississippi runoff values on primary tributaries range from 7 to 28 cm/yr; on the Brazos from 1 to 9 cm/yr; on the Snake from 3 to 55 cm/yr; and on the Gila from 0.1 to 4 cm/yr. These variations indicate significant variations in the geohydrology of 4 of the 6 basins, and suggest that there may also be marked variations in the relative concentrations and mineral composition of sediment yield from sub-basin areas.

In summary, subregional NASQAN station location and density on individual river systems and from one basin to another are somewhat arbitrary or primarily political. One element of partial consistency in their strategy is to locate NASQAN stations on "significant" tributaries near the point where they enter the main stream. Again though, what is and what isn't a significant tributary appears arbitrary on both an intra- as well an inter-river system basis.

C. Temporal Fluctuations in Sediment Transport

In order to examine the temporal sampling strategy for specific informational needs, it is first expedient to understand the nature of the measured quantity as a function of time. Examples of actual measurements made in the NASQAN program can also be viewed over a background of daily measurements of stream flow which is known to be closely related to sediment load. Alternative strategies can then be compared in terms of the return of the desired information.

Much research has been conducted on the mechanics of flow in alluvial streams, particularly on the relationship of the suspended sediment transport (Q_{ss}) to the hydraulic properties of the stream (e.g., Vanoni (1975)). Conceptually it is a simple matter to define the sediment transport as the flux of sediment which flows past a given cross section of the river in question. In practice, this quantity is difficult if not impossible to measure. Many factors contribute to this difficulty, such as bed-load transport along the interface of the sediment bed; ripples and dunes on the bed whose migration and induced turbulence make the sediment load a rapidly varying function of time; and, the need to measure and integrate the cross sectional distribution of sediment flux.

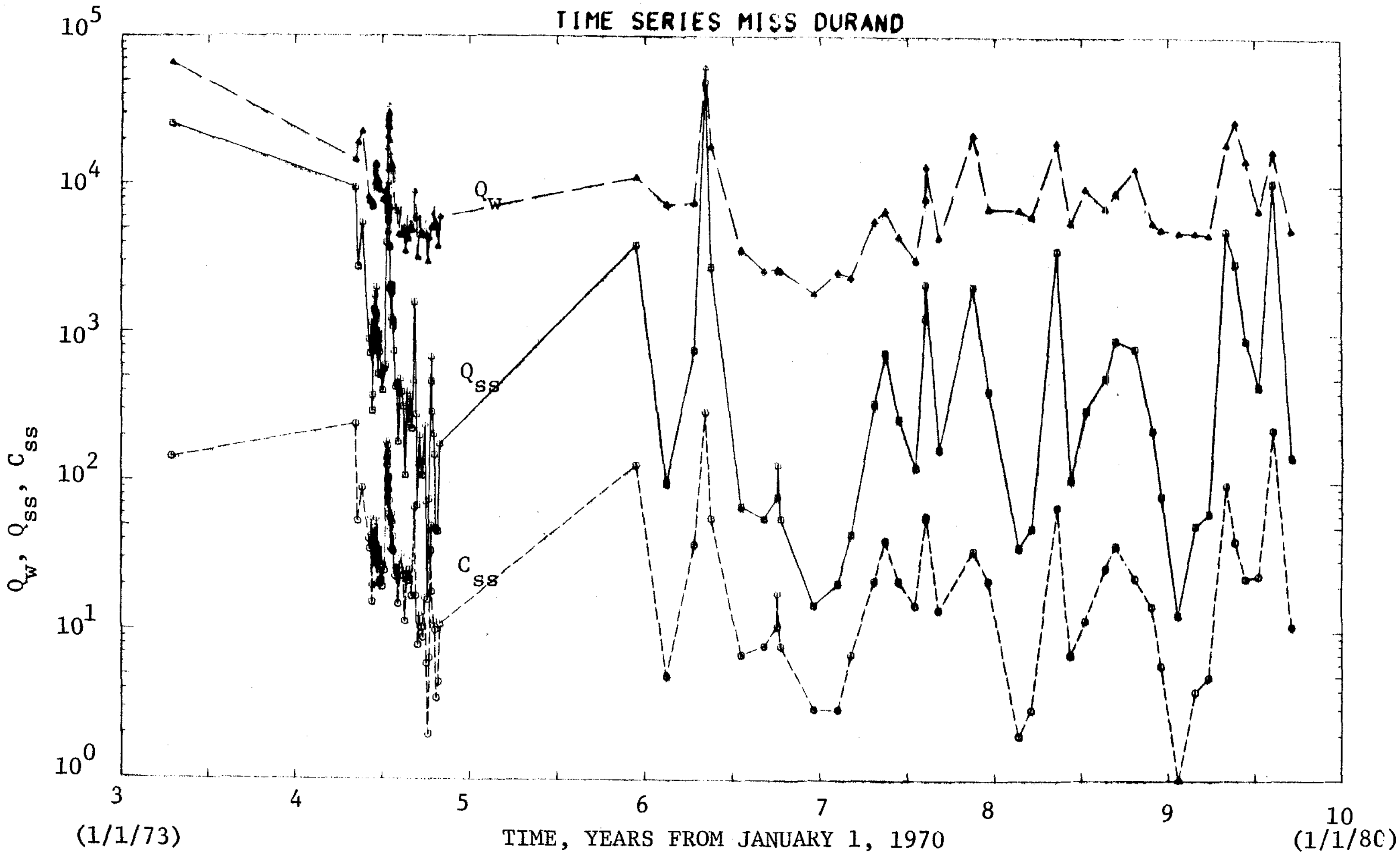


Figure 3.7 Time series of sediment discharge (Q_{ss}, tons/day), sediment concentration (C_{ss}, tons/day) and water discharge (Q_w, cfs) for the Mississippi River at Durand. (Note period in 1974 of much more frequent sampling.)

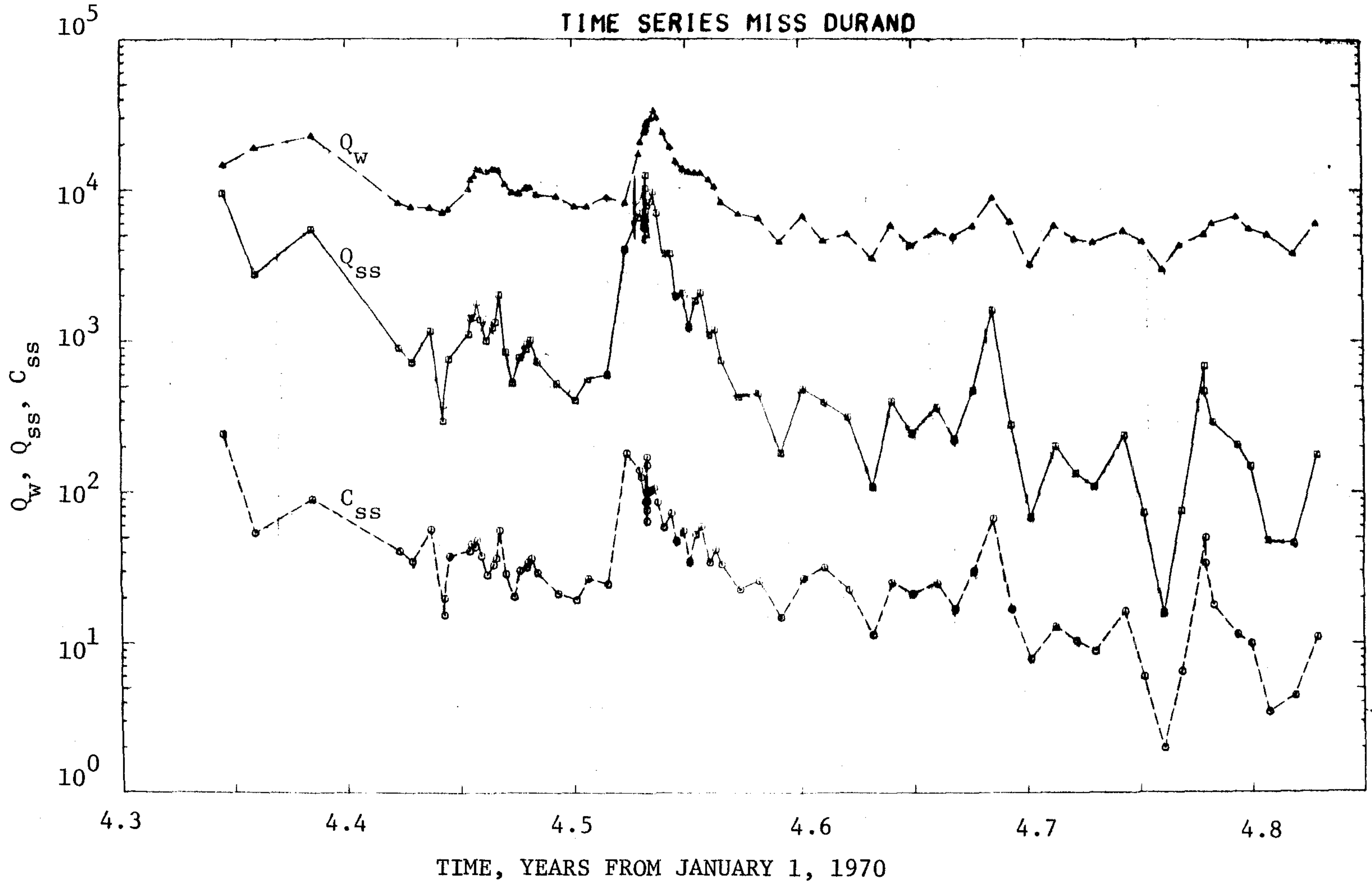


Figure 3.8 Time series of sediment discharge (Q_{ss}, tons/day), sediment concentration (C_{ss}, tons/day) and water discharge (Q_w, cfs) for the Mississippi River at Durand during period in 1974 of much more frequent sampling. (See Figure 3.7)

To better visualize the temporal variations of the sediment transport, a time series of instantaneous sediment data is shown plotted in Figure 3.7 for the sampling station at Durand along the upper Mississippi River. This particular time series is chosen because there was a period of time when very frequent samples were taken. Figure 3.8 shows that period magnified in the time axis. It can readily be seen that there are time variations much higher in frequency than any monthly measurement can possibly characterize. It can be concluded, therefore, that monthly instantaneous measurements <u>alone</u> cannot adequately characterize the sediment transport. In Chapter 4 we shall examine in more detail how a less frequent set of sediment measurements may be used in combination with a more frequent set of water discharge measurements in order to better estimate sediment yield.

It is well known that the suspended sediment concentration in a stream is positively correlated with the discharge. Physically this is easy to appreciate since an increase in discharge is accompanied by an increase in velocity and turbulence and hence the suspended sediment concentration. However, the ability to predict suspended sediment transport based on other hydraulic parameters has met with only limited success, especially in the field. One of the main reasons for this is the occurrence of different bed forms. More thorough discussions of the various aspects of this difficult subject can be found in Vanoni (1975) and Brownlie (1981).

Because Q_{ss}, the suspended sediment discharge, and Q_w, the water discharge, are positively correlated, it is instructive to examine the temporal variations of Q_w (for which there is daily measurement), and from it infer certain characteristics of the temporal variations of Q_{ss}. In fact, the combination of a small number of sediment measurements and a large number of water discharge determinations can form a powerful combination in any attempt at estimating the sediment yield, especially when coupled with background geologic and hydrologic information.

Figures 3.9, 3.10, and 3.11 show the daily water discharge measured at one station on the Clearwater, Susquehanna and Gila rivers respectively. In each of the figures, many years of flow are shown. The time series are displaced vertically for ease in visualization. The numerals are placed at the beginning of each water year, e.g., the tick mark for 1970 = October 1, 1969.

Comparison of the characteristics of the discharge time series shown in Figures 3.9, 3.10, and 3.11 clearly demonstrates the great disparity among the three rivers. The Clearwater shows a yearly pattern of runoff. The Susquehanna flows vary more haphazardly, while the Gila discharge can best be described as a series of spikes whose occurrences and magnitudes appear essentially random. In the case of the Gila river, there is very little likelihood that a monthly spot measurement would be sufficient to catch a representative range of flow of sediment concentration. Even for the other two rivers, where variations in flow are less extreme, a monthly instantaneous measurement would not be as desirable as measurements timed to coincide with

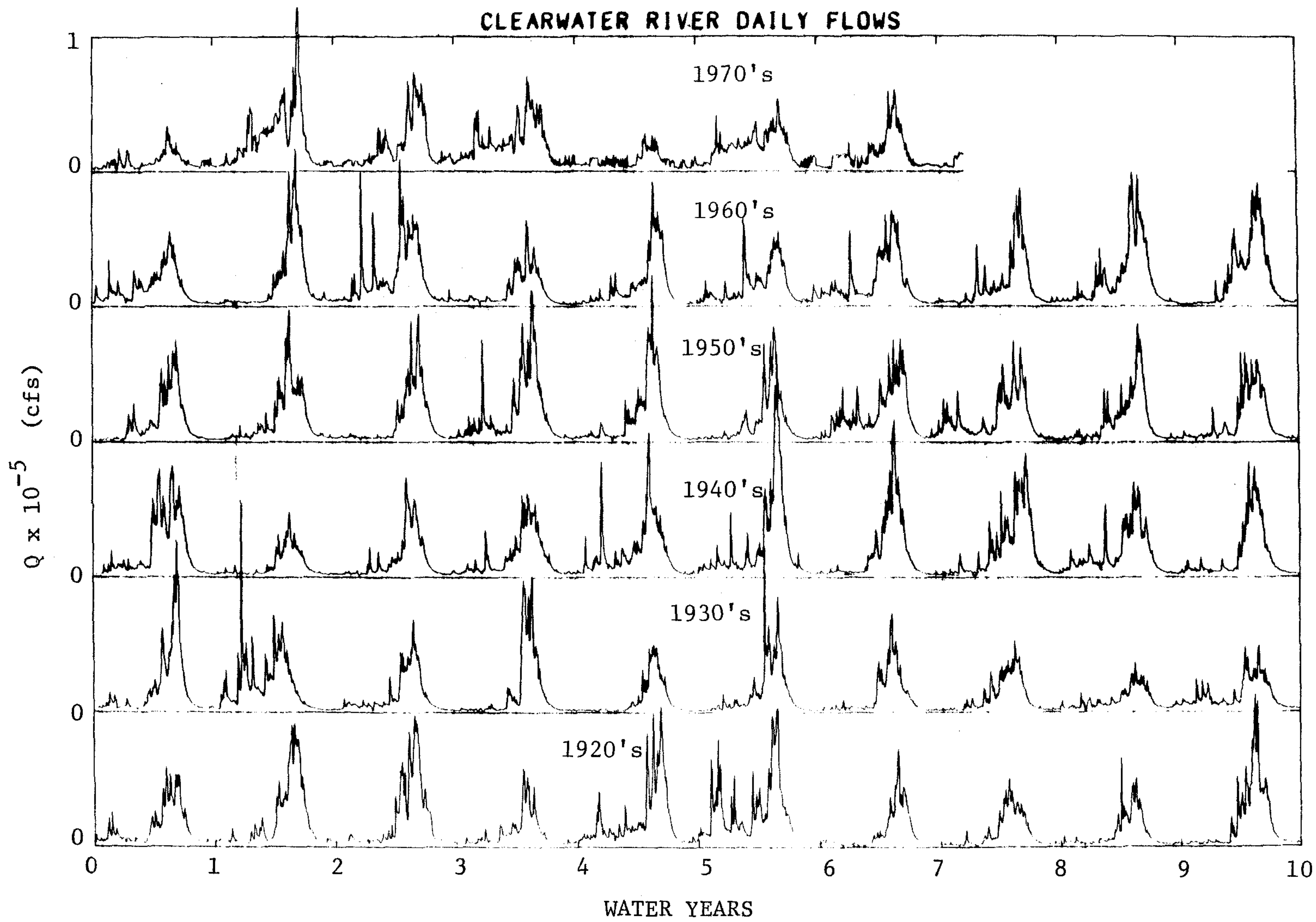


Figure 3.9 Time series of daily discharge for the Clearwater River at NASQAN station number 13342500.

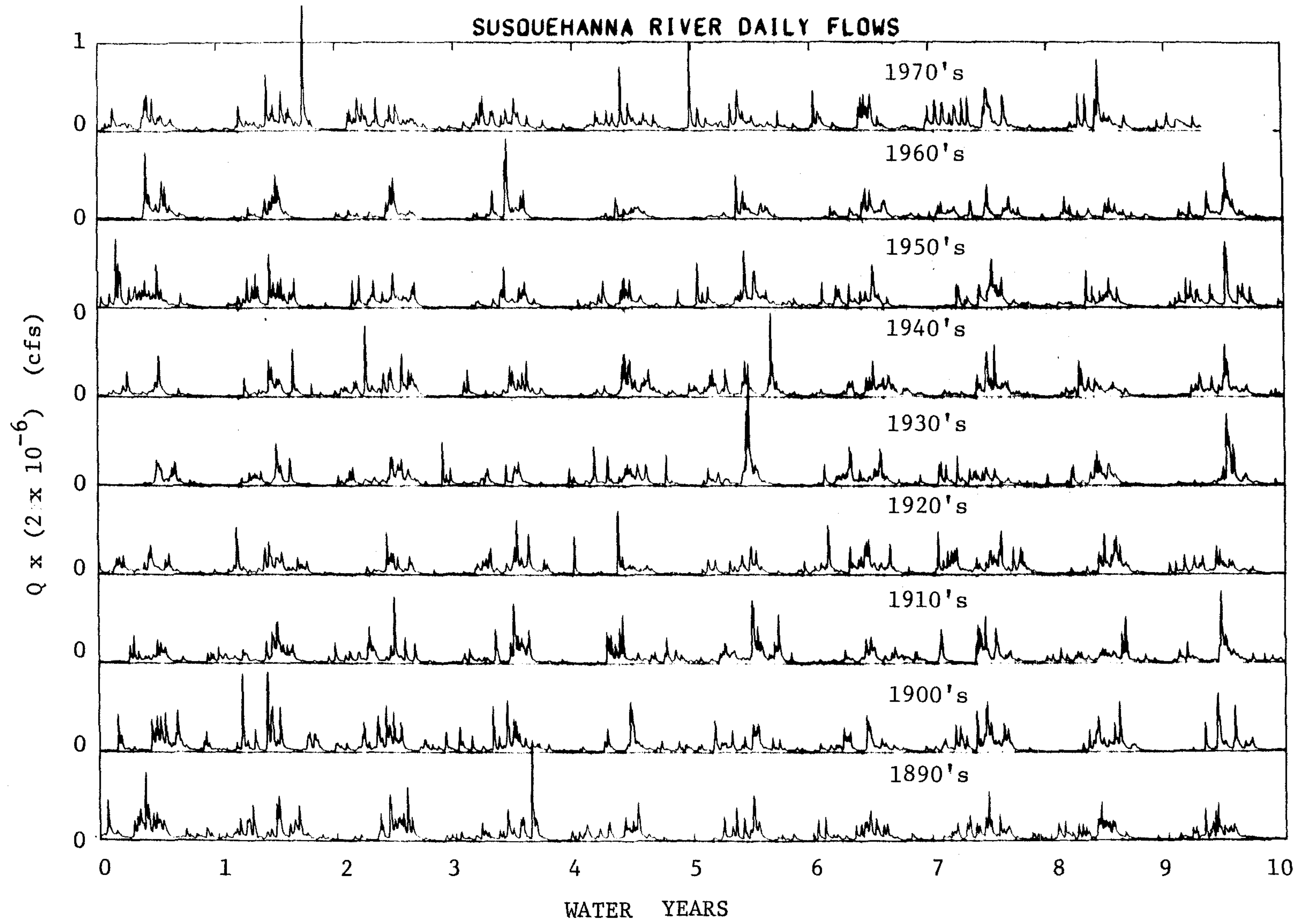


Figure 3.10 Time series of daily discharge for the Susquehanna River at NASQAN station number 01570500.

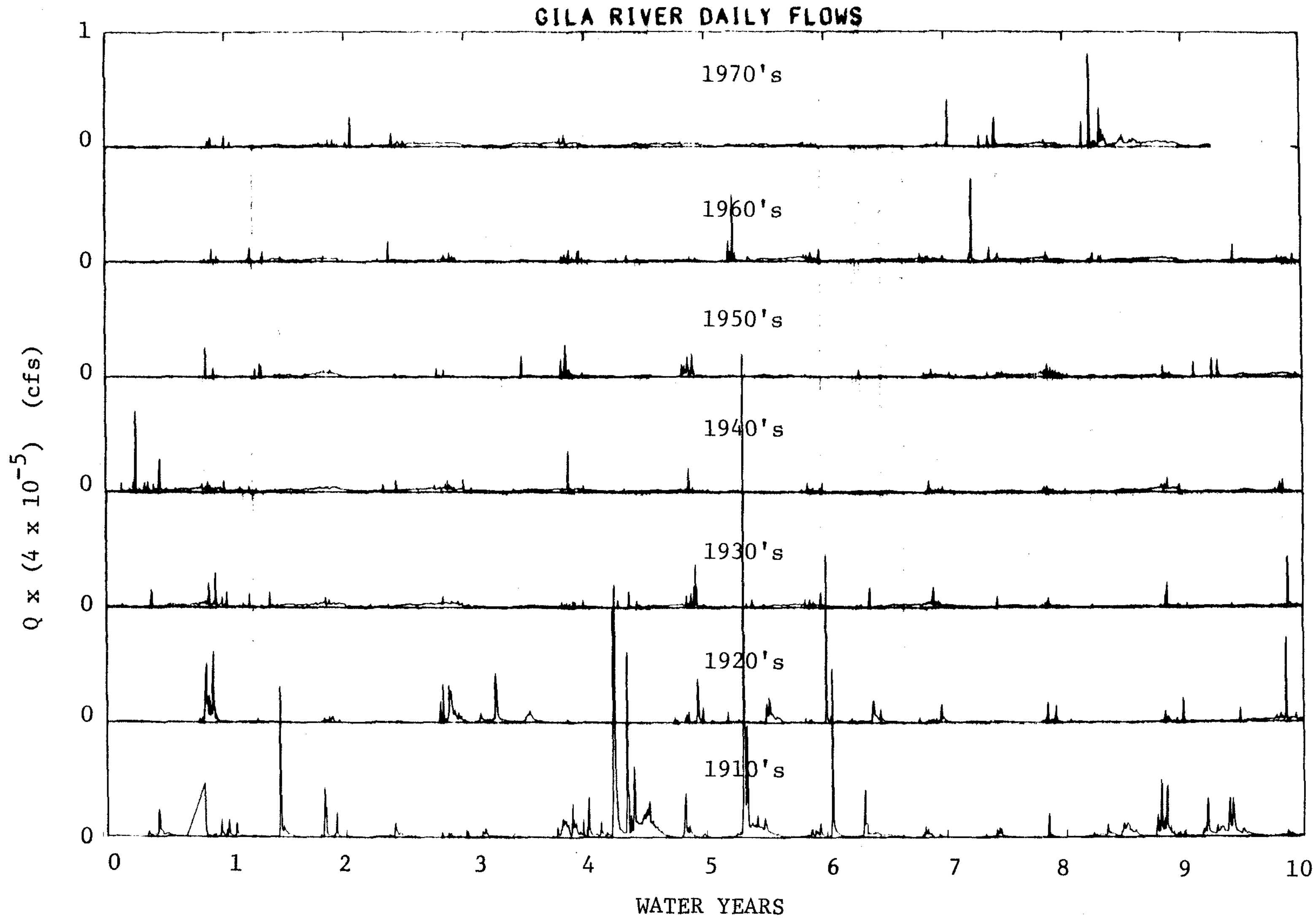


Figure 3.11 Time series of daily discharge for the Gila River at NASQAN station number 09474000.

the larger flows. The latter sampling strategy would provide a rational alternative to a fixed interval strategy when the transport (i.e., the flux of sediment or other substances) is of primary interest.

The power spectra for the time series of daily flows for the three rivers are shown in Figures 3.12, 3.13, and 3.14. The Clearwater and Susquehanna spectra show large variance contents in the lower frequencies while the Gila spectrum is effectively that of a set of Delta functions. These are as expected from examining the time series themselves.

In order to better visualize the temporal sampling of the suspended sediment concentration, Figures 3.15 and 3.16 show example time series of daily flows, with vertical lines indicating the times when suspended sediment was measured. It can be seen that for the case of the Clearwater Station, the sampling is more intensive during the period of higher flows, thus tending toward a strategy of weighting the sample data more toward high flows. With this strategy it could be expected that a determination of the suspended sediment rating curve might be more nearly correct at the higher flows leading to a more accurate estimate of sediment yield. Note that in the preparation of these figures, all the sediment measurements are included regardless of whether they were part of the NASQAN samples. If only NASQAN data were included these would appear as more or less evenly spaced at one-month intervals.

In summary, it is clear that the time scale over which

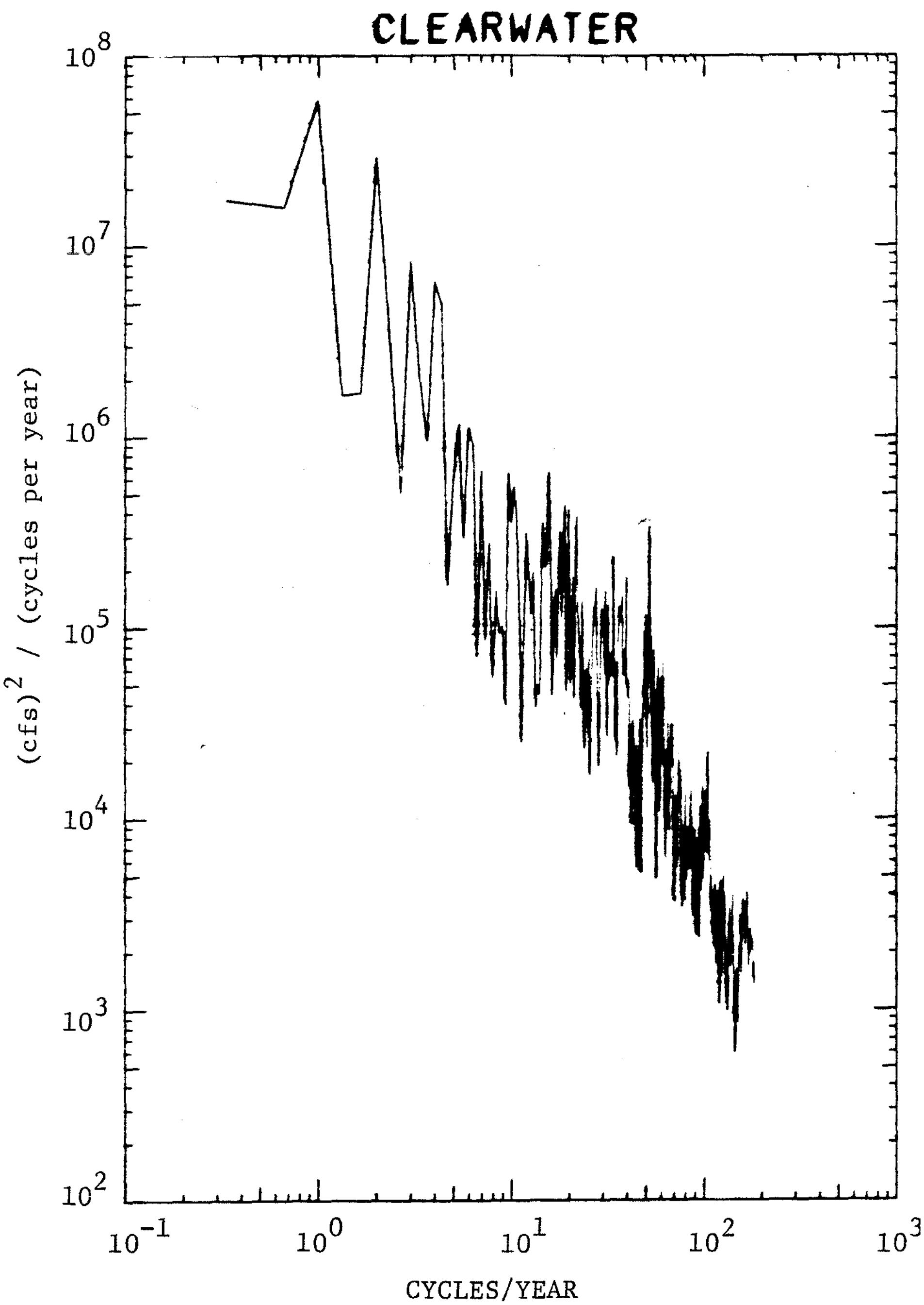


Figure 3.12 Power spectrum of daily discharge for the Clearwater River.

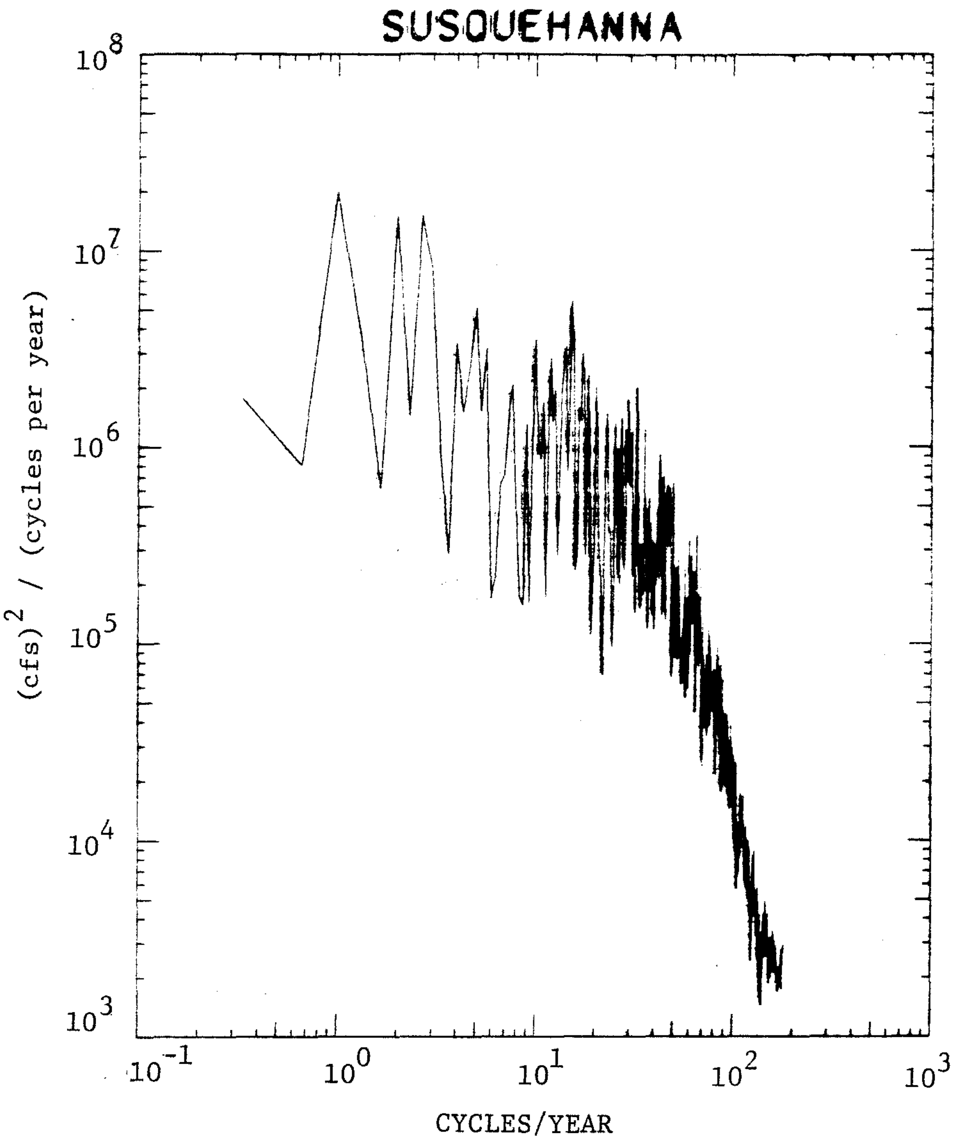


Figure 3.13 Power spectrum of daily discharge for the Susquehanna River.

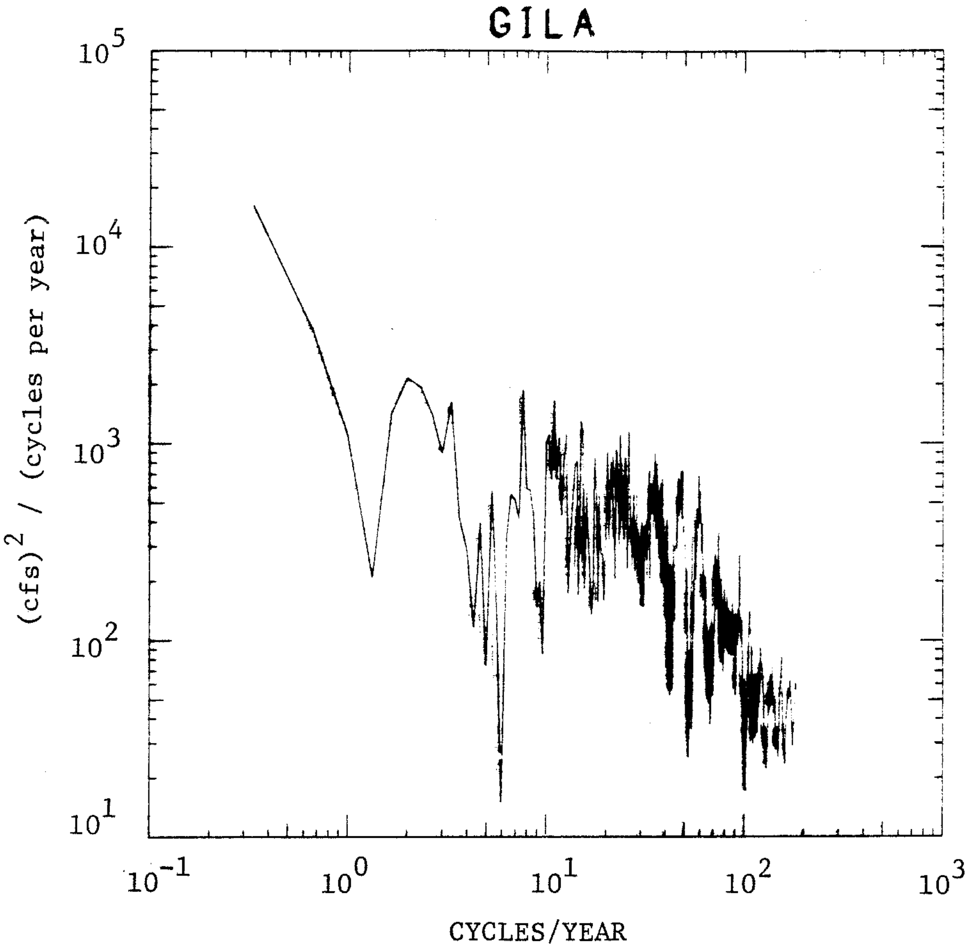


Figure 3.14 Power spectrum of daily discharge for the Gila River.

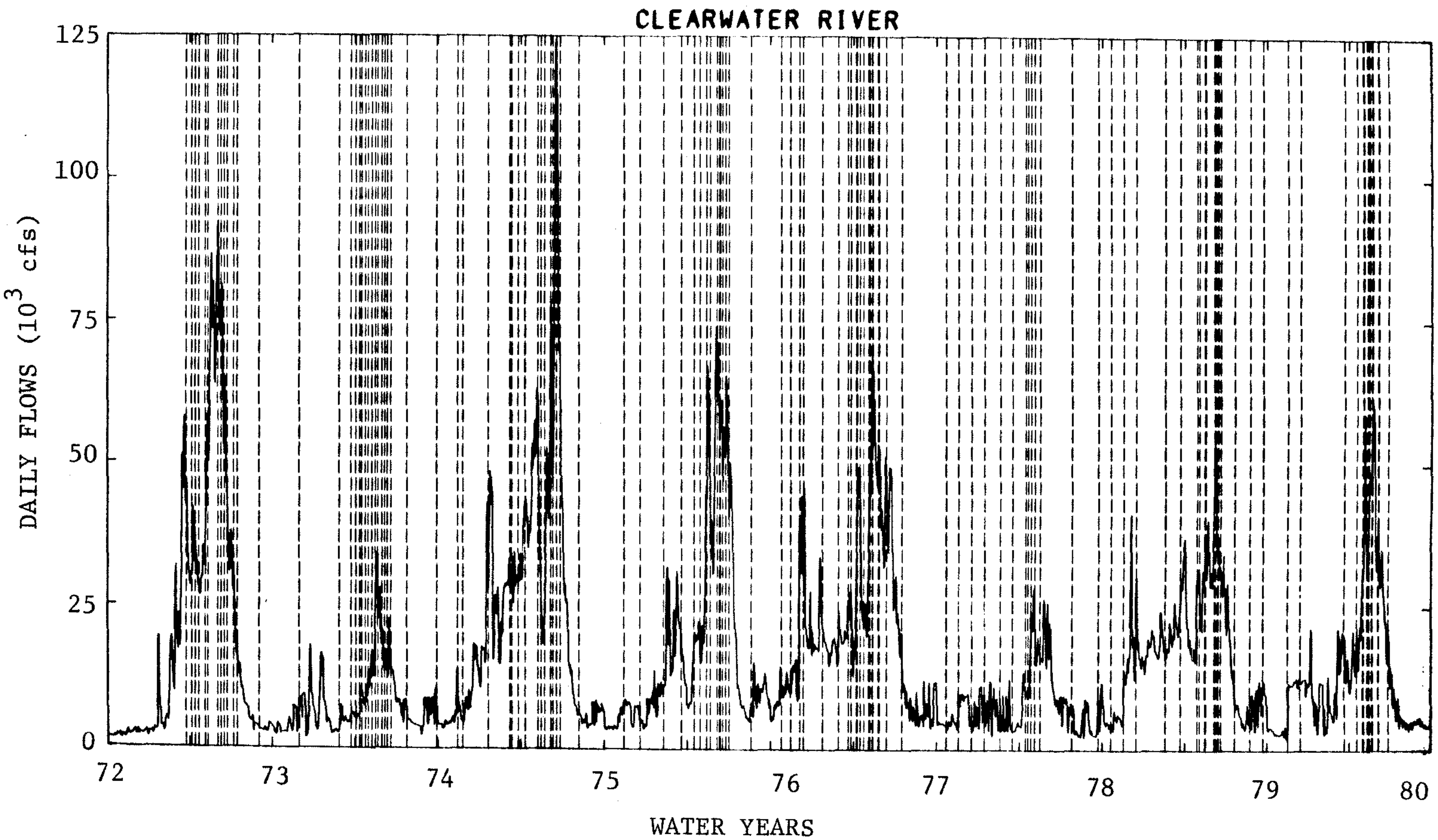


Figure 3.15 Time series of daily discharge. Dashed vertical lines indicate sampling times for sediment concentration data.

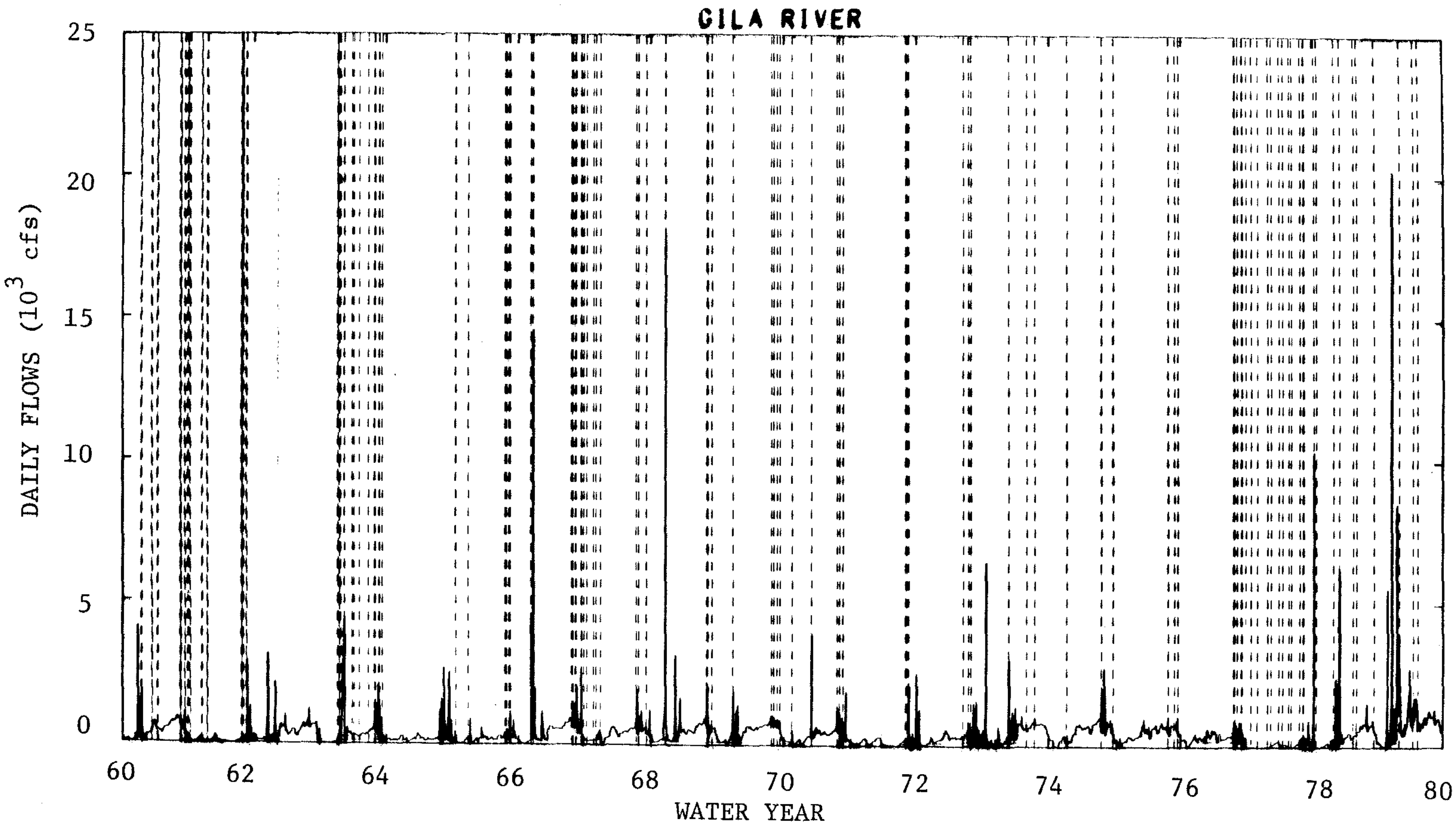


Figure 3.16 Time series of daily discharge. Dashed vertical lines indicate sampling times for sediment concentration data.

significant variations in suspended sediment concentrations can occur is quite short even for a large river such as the Mississippi. While this characteristic time varies from one river to another, it is certainly much less than one month. For rivers such as the Gila, this time scale would be very short indeed (only hours or a few days). Given that this is so, it would be difficult or impossible to assess the sediment transport on the basis of monthly measurements alone. However, if the sediment measurements are coupled with the daily water discharge measurements, it would be possible to better estimate sediment transport from the monthly NASQAN sediment data. This will be further discussed in Chapter 4.

D. Implications for Sampling Frequency

This section discusses the topic of sampling frequency as it pertains to the determination of suspended sediment concentration in the NASQAN stations. Present sampling strategy calls for the taking of monthly samples where each sample consists of the determination of the suspended sediment concentration in several vertical profiles in the cross section of the river at the sampling station. The measurement in each vertical profile is accomplished by means of a depth-integrating sampler which is designed to measure the flow-weighted average suspended sediment concentration c_a given by

$$c_a = \frac{\int cudz}{\int udz}$$

where c and u are the suspended sediment concentration and flow velocity for any z, (the vertical coordinate) and the integral is over most of the water depth. The several values thus obtained along the chosen verticals can then be integrated to obtain an overall flow-weighted average suspended sediment concentration (Q_{ss}/Q_w).

This particular method of measurement implies that the quantity of primary interest is the flux or transport rate of suspended sediment rather than the concentration itself. In the next chapter we will discuss how one can utilize the measured sediment concentration data to estimate the sediment yield. It will be seen that when used in combination with the daily water flow data, the relatively sparse sediment data can provide an estimate of the sediment yield which can only be improved by much more frequent sampling. When viewed alone as a time series, monthly sediment data cannot capture the temporal variations properly. Without any appeal through correlations with more frequently sampled data (i.e., water discharge), analysis of temporal changes, such as trend analysis, can be misleading. Fortunately, continuous water discharge measurements are made at all NASQAN stations. These should always be part of any analysis of the sediment data.

CHAPTER 4

DETERMINATION OF SEDIMENT YIELD BY NASQAN DATA

A. Introduction

In this chapter, we shall examine in some detail one of the important uses of the sediment data: estimation of the annual sediment yield. First, using data from the stations on the six river systems chosen in Chapter 3, conventional estimates of sediment yield via suspended sediment rating curves will be discussed.

For some of the sampling stations, there exists daily measurements of sediment concentration. These afford a means of testing how well sediment yield can be estimated on the basis of (i) different methods of suspended sediment rating and (ii) different sampling frequencies. In the following, several unconventional sediment rating methods are explored with the intent to investigate whether the sediment yield can be better estimated either by a different method or more frequent samples.

B. Conventional Suspended Sediment Rating Curves

When suspended sediment transport rate Q_{ss} is plotted against the water discharge Q_w on log-log graph paper, the points for a given sampling station often fall about a straight line. When such a straight line is fitted to the points, the result is referred to as a suspended sediment rating curve. There is, of course, no basis for requiring that the rating curve be straight. Any monotonic curve can be empirically justified if it closely approximates the data. However, there is invariably a certain amount of scatter about the regression line. A question of interest is obviously why such scatter should occur. If an attempt is made to develop suspended sediment rating curves for a number of sampling stations along an alluvial stream or for a number of different streams, one finds that the goodness of fit of the points to a line can vary substantially from one case to another.

It is a simple matter to routinely develop suspended sediment rating curves for each of the sampling stations in the NASQAN system. The procedure boils down to the computation of the means, variances and covariances of the logarithms of the suspended sediment and water discharges. From these, the parameters for the regression line can be calculated. It is also possible to calculate a measure of the goodness of fit in the so-called coefficient of determination which in this case is effectively equivalent to the square of the correlation coefficient. This is not the purpose of the present investigation. (A good start has already been made toward this goal by Brown (1978) who showed that the NASQAN stations can be divided into several groups according to how well suspended sediment rating curves can be defined.)

Sediment in suspension is conveniently divided into two portions by size. The fine material, usually defined to be smaller in diameter than 0.064mm and known as wash load, can be thought of as not participating in dynamic interaction with the stream bed. The concentration of this fine material (silt and clay) in the stream depends primarily on the supply of sediment. The flow is generally not the limiting factor. The coarse material (sand), which is larger than 0.065 mm can be called bed-material load, is usually in dynamic equilibrium with the sand on the stream bed, or adjusting toward an equilibrium. The concentration of bed material in the stream can therefore be expected to be a function of the stream flow. When a suspended sediment rating curve is sought, one is implicitly seeking this relationship.

However, if the total sediment concentration is used then the wash load is also included, which can degrade the goodness of fit. The question is raised as to whether suspended sediment rating is improved if the wash load is first subtracted from the data so that only the sand fraction is rated. In an attempt to answer this question, we performed suspended sediment rating calculations for a number of stations along six rivers across the country using both the total suspended sediment load and the sand fraction. The results are shown summarized in Tables 4.1 and 4.2, as explained below.

Table 4.1 shows the results for the total concentration including both sand sizes and wash load sizes. Table 4.2 shows the results for the sand sizes only. In each of the tables, column 1 gives the station designation for the data, column 2 shows the total number of data points available for analysis for this station. Columns 3 and 4 respectively give the values for A and B in the equation for suspended sediment rating

TABLE 4.1

Summary of Conventional Suspended Sediment Rating Calculations for the Six Selected River Systems

Station	Number of Data Points	A*	B*	Coefficient of Determination R^2
Brazos River				
08080500	13	0.15541	1.3955	0.92154
08082000	24	1.74142E-03	2.4787	0.79394
08082500	28	7.62835E-04	2.4385	0.80023
08088000	11	6.88088E-03	1.8977	0.95056
08098290	47	5.94391E-04	1.8278	0.86544
08106500	8	1.78374E-02	1.4674	0.81841
08116650	60	8.87631E-04	1.8178	0.90907
Mississippi River				
05267000	33	4.94970E-02	1.0160	0.57214
05330000	46	1.07286E-02	1.4946	0.93378
05331000	45	1.84015E-02	1.2416	0.60091
05340500	53	4.71425E-04	1.3865	0.44488
05369500	131	4.19321E-06	2.0693	0.82891
05378500	7	5.06845E-04	1.4930	0.99597
05382000	19	1.76003E-03	1.5305	0.86106
05407000	33	4.02920E-06	2.0416	0.70938
05420500	34	2.38097E-02	1.1565	0.71273
Gila River				
09431500	97	9.45968E-03	1.6649	0.49053
09466500	26	2.40898E-02	1.7977	0.79712
09473500	91	10.689	1.3868	0.68323
09474000	120	0.53577	1.5829	0.56345
09510000	19	1.4658	0.43422	7.34990E-02
09518000	24	0.76066	0.85576	0.53680
09520700	30	3.86719E-04	2.0391	0.93510
Mobile River				
02420000	44	5.07768E-04	1.4539	0.89971
02429500	56	1.74599E-05	1.8376	0.87256
02449000	44	5.50181E-04	1.6219	0.92320
02466031	9	3.08223E-03	1.2690	0.87875
02469762	48	1.43794E-05	1.8990	0.94056
Snake River				
13022500	46	9.06352E-07	2.3193	0.83282
13037500	13	9.58827E-04	1.3113	0.52295
13154500	59	8.83901E-06	1.9038	0.56049
13213000	42	1.37609E-02	1.3244	0.62878
13213100	37	0.14056	0.93854	0.24711
13269000	22	1.00971E-02	1.2296	0.15583
13290450	3	(8.08251E-24	5.8037	0.96648)#
13317000	53	3.71611E-07	2.2474	0.75561
13342500	127	1.39103E-06	2.0277	0.78342
13353200	69	3.07685E-07	2.0613	0.73861
Susquehanna River				
01540500	66	1.65174E-05	1.9008	0.82855
01553500	63	5.89784E-05	1.7081	0.71724
01567000	46	0.15337	1.0812	0.65849
01570500	227	6.73199E-06	1.8910	0.85288
01578310	16	1.97091E-10	2.7179	0.92286

*In equation $Q_{ss} = AQ_w^B$. Q_w in cfs, Q_{ss} in tons/day.

#Should be disregarded due to inadequate quantity of data

TABLE 4.2

Summary of Conventional Suspended Sediment Rating Calculations for the Six Selected River Systems. For Sand Sizes only

Station	Number of Data Points	A*	B*	Coefficient of Determination R^2
Brazos River				
08080500	9	5.21790E-03	1.2865	0.80181
08082000	22	3.54857E-04	2.1889	0.80280
08082500	23	1.14902E-04	2.1123	0.76540
08088000	9	2.91208E-04	1.9177	0.94853
08098290	45	1.85551E-06	2.3192	0.88180
08106500	7	9.81011E-04	1.3460	0.67866
08116650	50	4.19497E-05	1.8499	0.76463
Mississippi River				
05267000	24	3.34059E-03	1.0805	0.57118
05330000	29	3.39957E-03	1.4323	0.84175
05331000	28	4.23576E-03	1.2052	0.49567
05340500	17	3.28550E-02	0.79587	4.23797E-02
05369500	41	5.23899E-09	2.7170	0.75260
05378500	4	(1.64597E-04	1.3975	0.71187)#
05382000	11	3.66277E-06	2.1420	0.91142
05407000	26	5.32609E-07	2.1641	0.64166
05420500	12	0.36962	0.65610	0.72357
Gila River				
09431500	27	4.27112E-04	1.9769	0.48115
09466500	24	1.22933E-03	2.0233	0.86880
09473500	61	1.61626E-02	1.9217	0.85938
09474000	103	1.57196E-02	1.6579	0.69058
09502000	3	(5713.6	-1.1115	0.00000)#
09510000	16	3.76627E-02	0.71396	0.41627
09518000	24	0.31458	0.61709	0.10335
09520700	30	1.00672E-04	2.1476	0.92923
Mobile River				
02420000	42	1.30211E-06	1.7872	0.78441
02429500	43	2.94357E-11	2.8820	0.83279
02449000	41	6.74219E-07	2.0857	0.89047
02466031	9	2.33708E-04	1.0900	0.75377
02469762	41	1.47828E-09	2.5675	0.88403
Snake River				
13022500	36	5.52970E-07	2.2224	0.78821
13154500	35	2.10946E-03	1.0927	5.4261E-02
13213000	30	2.90853E-05	1.9004	0.65581
13213100	31	2.23956E-05	1.6843	0.71260
13269000	15	1.32088E-14	3.8326	0.67612
13317000	31	7.58898E-08	2.2821	0.62975
13342500	50	3.58896E-12	3.1572	0.80826
13353200	40	1.25316E-07	1.8432	0.62763
Susquehanna River				
01540500	56	7.34456E-06	1.7259	0.72045
01553500	37	6.21512E-06	1.7590	0.64801
01567000	41	1.68830E-02	1.0904	0.83394
01570500	99	2.06703E-07	2.0062	0.79198

*In equation $Q_{ss} = AQ_w^B$. Q_w in cfs, Q_{ss} in tons/day.

#Should be disregarded due to inadequate quantity of data

$$Q_{ss} = AQ_w^{\ B} \tag{1}$$

The last column marked R^2 is the coefficient of determination in the logarithmic fit. Numerically R^2 is the same as the square of the estimated linear correlation coefficient between log Q_{ss} and log Q_w. It can be seen that in almost all cases, the rating curves based on sand fraction only actually showed worse fit than the corresponding rating based on the total suspended sediment load. We must conclude, therefore, that the presence of the fine material or wash load does not explain any of the scatter in the data.

Another possible reason for the scatter is the effect of other variables not taken into account in the simple regression. Unfortunately, only a limited investigation into this aspect is possible, since not many variables which could be responsible have been simultaneously measured. Two separate hypotheses were examined having to do with: (i) the dependence of suspended sediment rating on time, i.e., year-to-year variations, and (ii) the dependence of suspended sediment rating on season, i.e., month-to-month variations. In this regard, we have plotted the suspended sediment rating data for each of the stations in Tables 4.1 and 4.2 and then highlighted each month or each year in order to determine if there was any discernable improvement. This involved the examination of a large number of graphical results and the conclusion is somewhat subjective, but we were unable to notice any significant improvement.

In summary, it might be concluded based on the data scatter for NASQAN sediment data (as exemplified in Table 4.1), that the conventional technique of suspended sediment rating can be used to estimate sediment transport for many, but not all, of the NASQAN stations. The reasons why there is such large scatter in the data for many of the stations have not been identified.

It is straightforward to obtain a suspended sediment rating relation on the basis of empirical data. Brown (1978) made a preliminary examination of conventional suspended sediment rating relations for a large number of NASQAN stations. Using only the coefficient of determination as a measure of the success of such an analysis, he concluded that suspended sediment rating analysis would be successful for some stations and not others.

C. Modified Suspended Sediment Rating Curves

The ability to estimate accurately the sediment discharge or transport in a river system has been described by Vanoni (1975) as the most important practical objective of research in sedimentation. Two generally different classes of procedures are available to the engineer faced with the task. On the one hand, there are numerous "formulas" which predict sediment discharge based on knowledge of flow variables. These are summarized and discussed in Vanoni (1975) and Brownlie (1981) and will not be recapitulated here. On the other hand, estimates of sediment discharge can also be made directly from empirical data for the particular locations of interest. This latter method is more reliable since it is based on actual *in situ* data.

In this section, we shall consider how one may estimate the sediment yield for a stream from measurements of sediment concentration at isolated sampling times. In particular, we shall investigate how one may utilize the combination of these sediment concentration measurements together with daily water discharge measurements to arrive at a better estimate than might be possible with the sediment data only.

The concept of the suspended sediment rating curve where the sediment discharge is expressed as a power relation to water discharge has provided river engineers with a useful tool for making estimates of sediment transport for decades. Its use implicitly assumes a unique relationship between the two variables. Unfortunately, this is not the case. Brooks (1958) has demonstrated that the solution to the problem of flow in a sediment-laden fluid in an open channel is not always unique, given depth and slope. This implies that for some conditions, multi-valued rating curves would result. Since his laboratory results, such multi-valued rating curves have been found in the field.

Sediment concentrations are measured on a ′spot′ basis once per month on all NASQAN stations. Additionally, for some stations, actual daily measurements of sediment concentration are made. For these stations, it is possible to test whether (i) more frequent sediment sampling would improve the estimate of sediment transport and sediment yield and (ii) whether some modifications of the methodology of developing suspended sediment rating relations would improve these estimates. In this section these two questions will be examined empirically.

If it is assumed that the daily water and sediment discharge measurements are correct and that the annual sediment yield is given by the sum of the daily measurements of sediment discharge over the year, three alternative approaches may be used to develop a suspended sediment rating relation:

(a) straight unweighted suspended sediment rating
(b) weighted suspended sediment rating
(c) interpolated suspended sediment rating

For case (a), simple linear regression would yield a rating relation of the form

$$Q_{ss} = AQ_w{}^B \qquad (2)$$

where Q_{ss} = suspended sediment discharge, Q_w = water discharge, A and B are coefficients determined in the regression analysis. In performing the regression analysis, one can use all the daily data available, or just a portion of the data. In particular, if only one data point is used per month, it is still possible to develop a regression relation. The question of an appropriate sampling frequency can therefore be addressed by examining the results as one increases the number of samples used in developing the regression relation.

For case (b), the same regression procedure as case (a) is used except the various data points can be given unequal weights. On the basis of the argument that the suspended sediment discharge is influenced by seasonal factors other than water discharge alone, those measurements which were made nearer the time when a specific estimate of sediment discharge e.g., daily value, is being calculated should be given a higher weighting. Again, the question of sampling frequency can be addressed by selecting appropriate subsets of the original data.

In both the above alternatives, even if all the daily data were used in obtaining the suspended sediment rating curve, computation of the estimated suspended sediment discharge will still differ from the actual measured one. This is because the rating relation is a fixed one about which the data scatter. To overcome this problem, a third scheme is possible whereby the rating relationship is shifted (by changing A in equation 1 without changing B) to coincide with the actual data whenever data are available. Where data are not available, the value of A used is interpolated between straddling known data values. This represents the methodology designated as "interpolated," or case (c) above. Again, one can use all the daily data in which case the method gives the same estimate of sediment yield as the sum of the daily measurement. Alternatively, one can use a subset of the daily measurements as the starting point and use the shifted and linearly interpolated rating curves for the remainder.

All these three methods have been tested empirically for several levels of data decimation. The relationships for the sediment to water discharge data for the two stations (on the Susquehanna and Gila) are shown in Figures 4.1 and 4.2., i.e., case (a), "straight

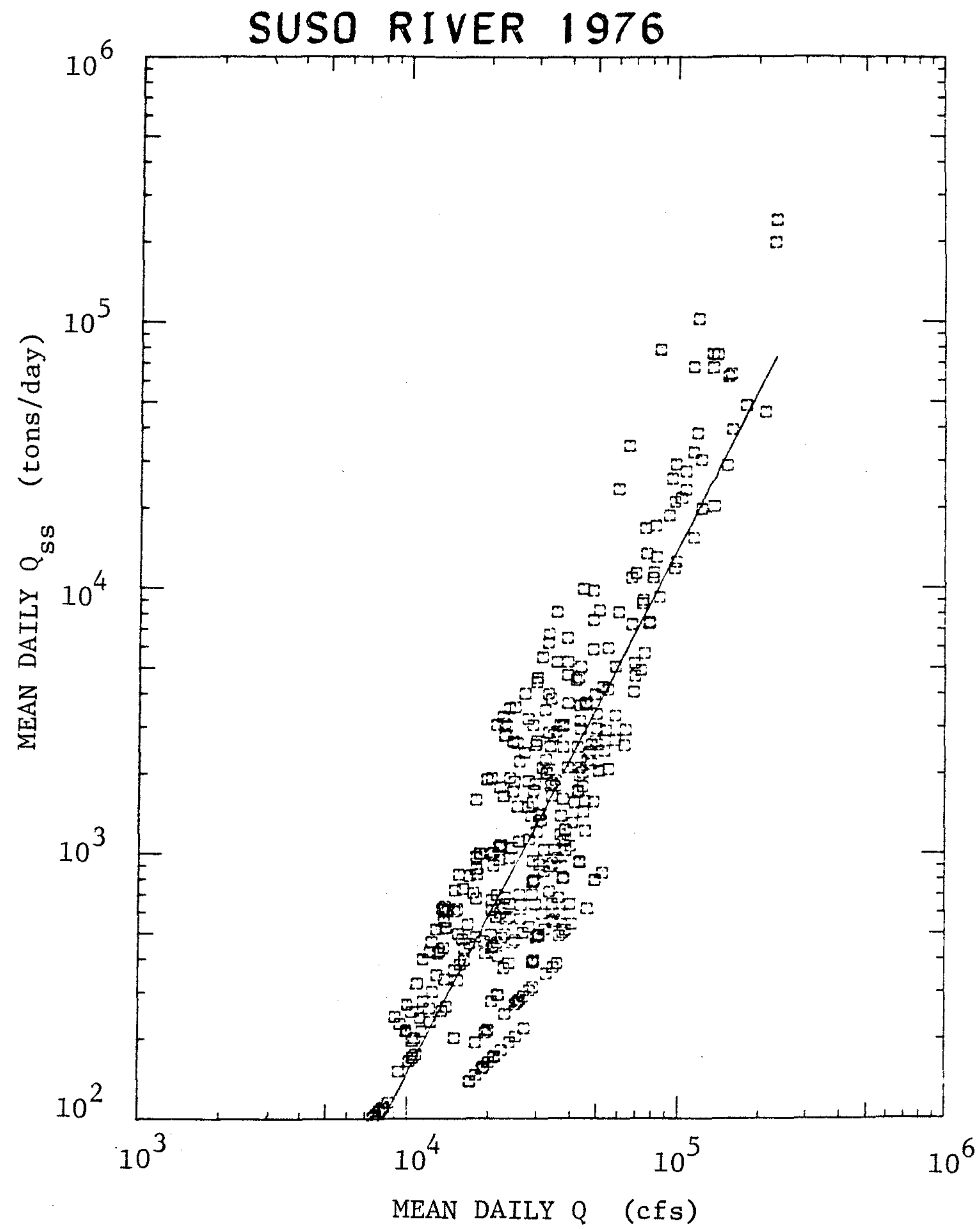


Figure 4.1 Sediment rating for the Susquehanna River based on daily water discharge and suspended sediment measurements for NASQAN station number 01570500.

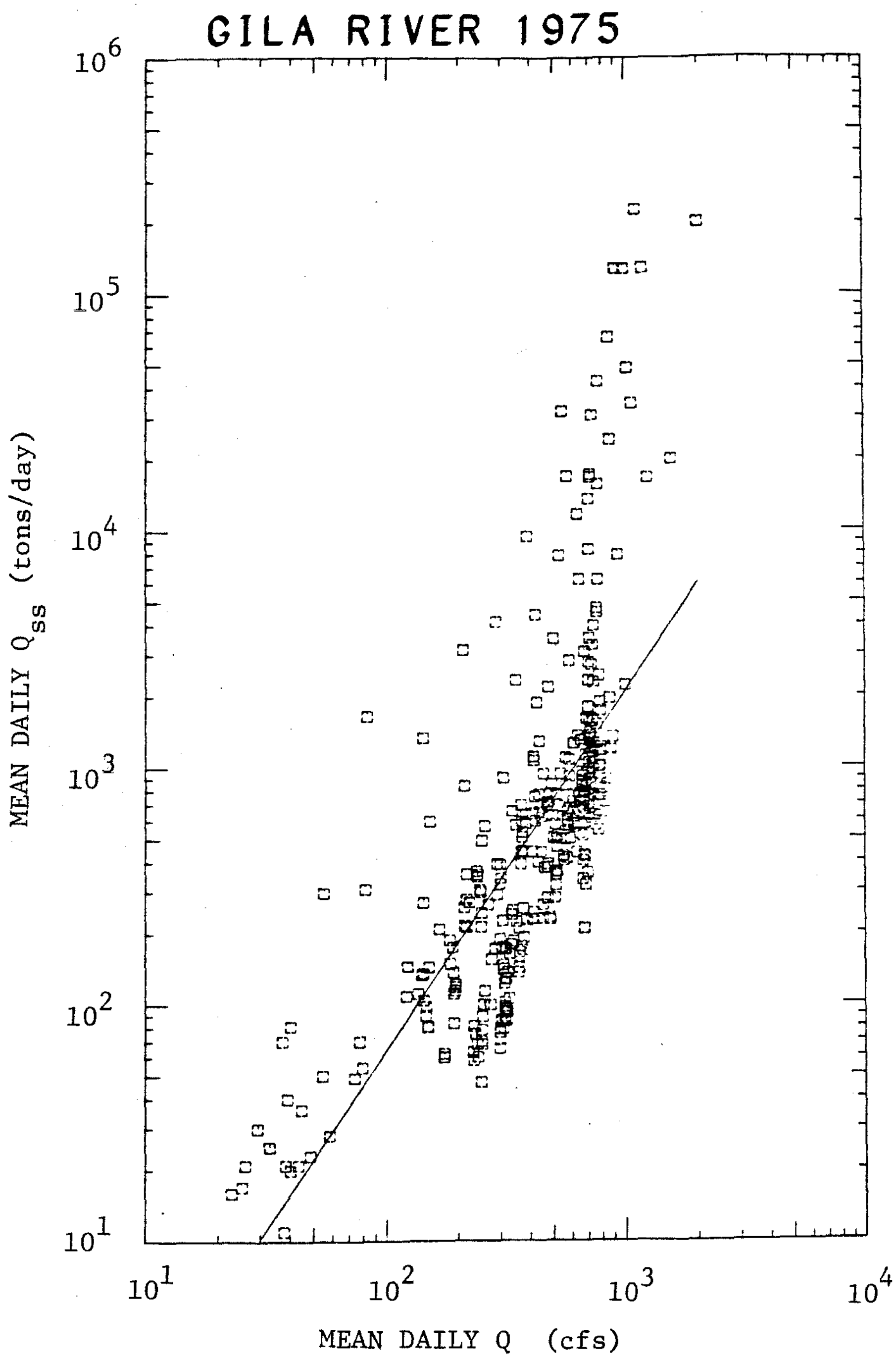


Figure 4.2 Sediment rating for the Gila River based on daily water discharge and suspended sediment measurements for NASQAN station number 09474000.

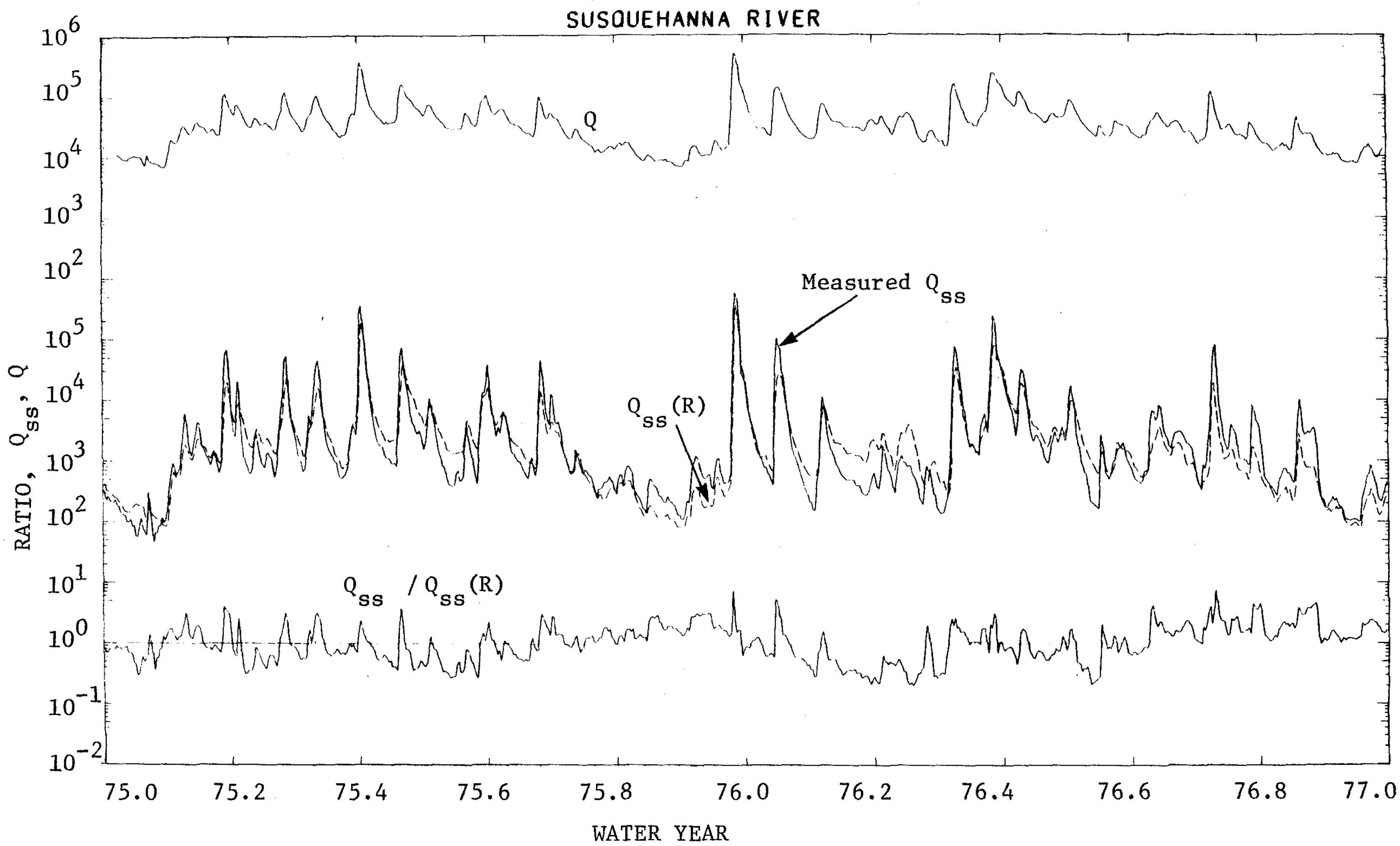


Figure 4.3 Comparison of predicted and actual daily sediment discharges for the Susquehanna River based on sediment rating method (unweighted).

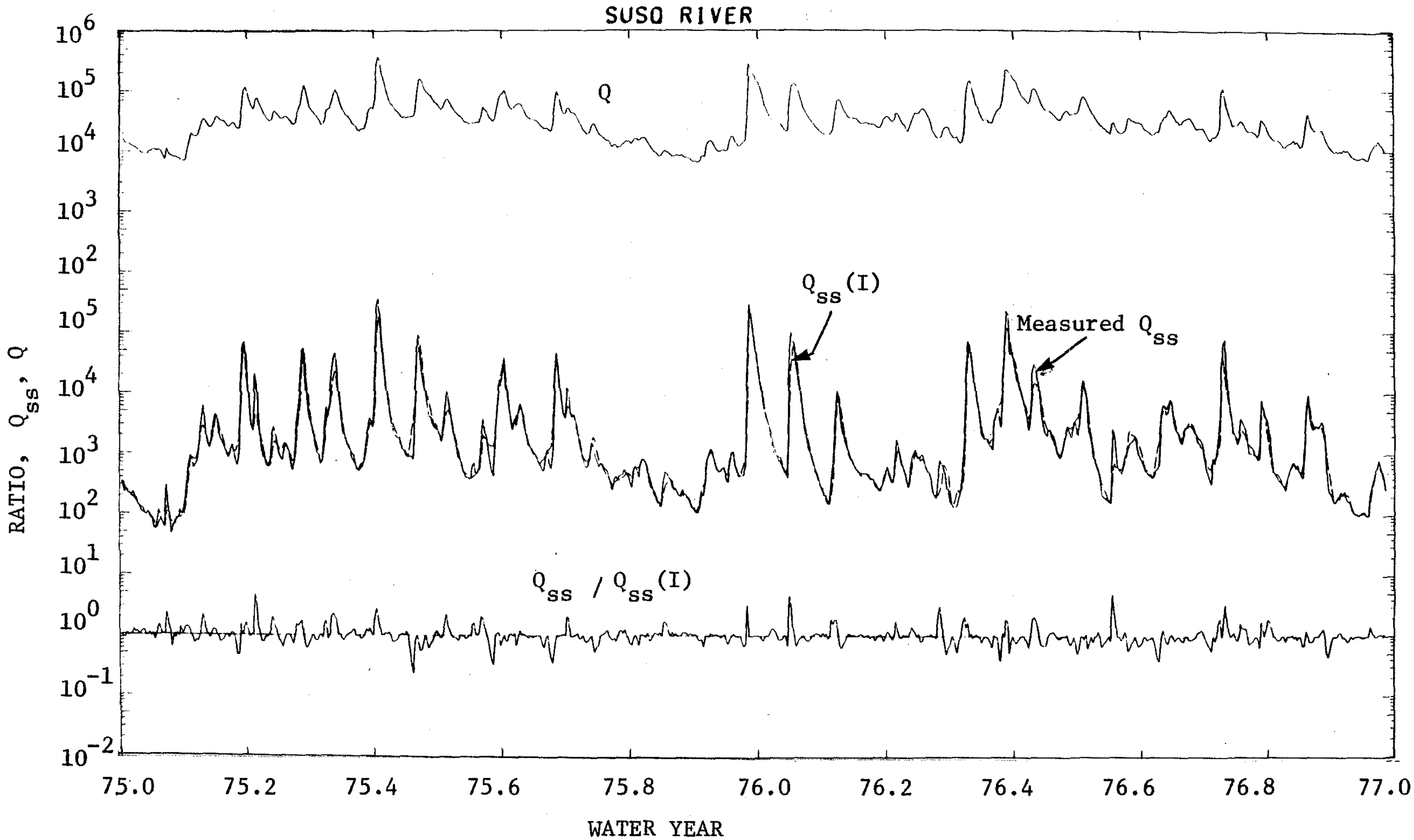


Figure 4.4 Comparison of predicted and actual daily sediment discharge for the Susquehanna River based on sediment rating method (interpolated).

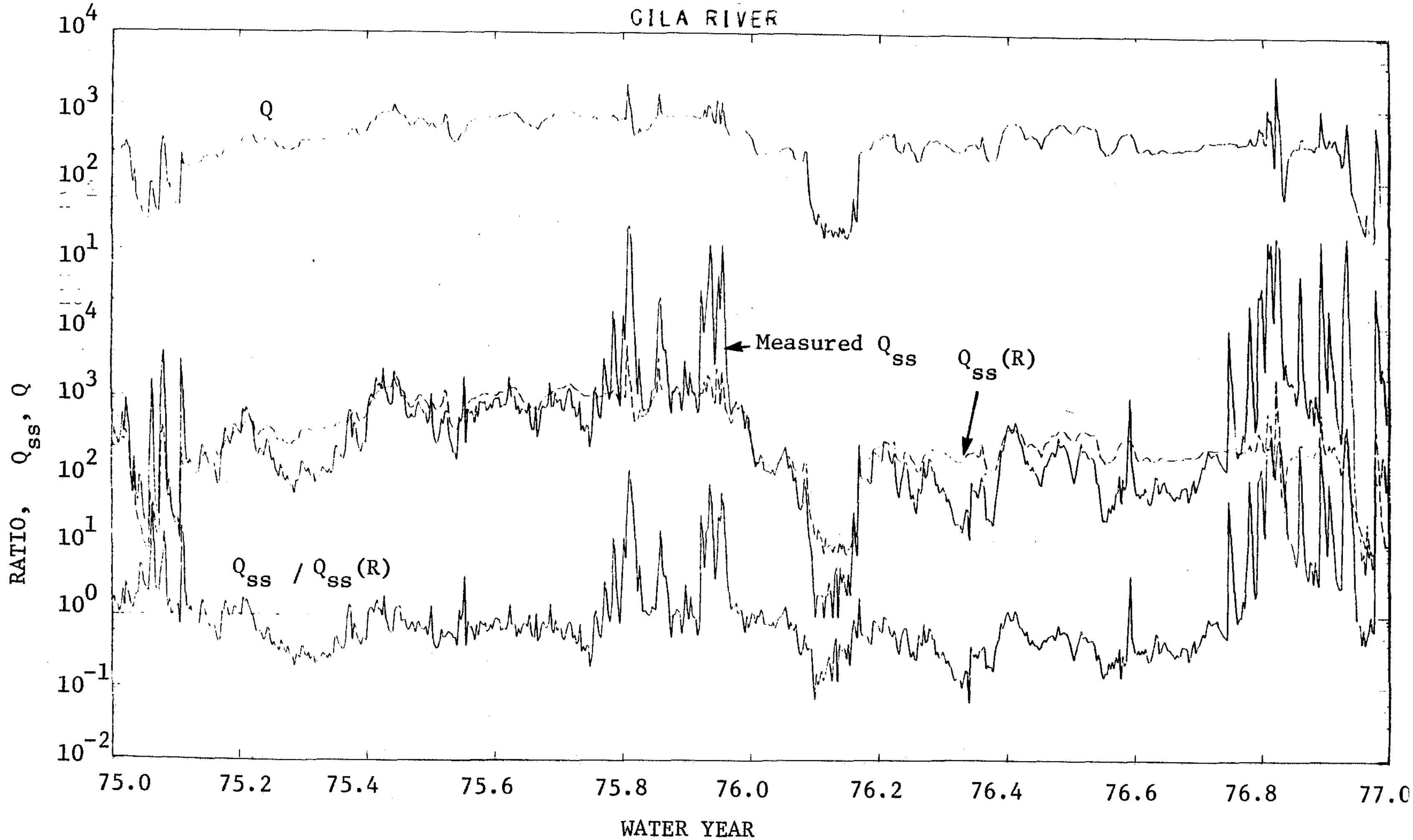


Figure 4.5 Comparison of predicted and actual daily sediment discharges for the Gila River based on sediment rating method (unweighted).

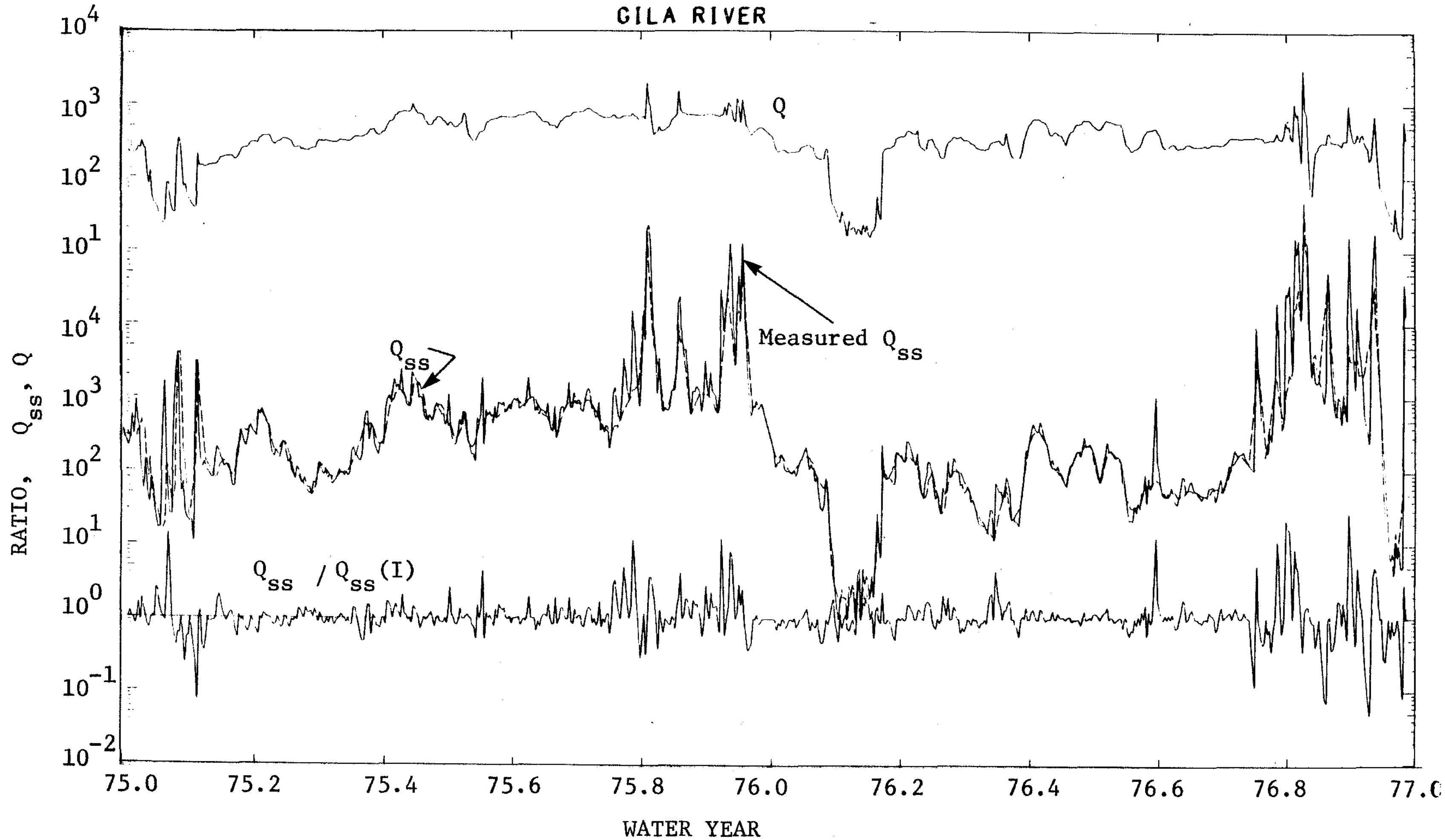


Figure 4.6 Comparison of predicted and actual daily sediment discharge for the Gila River based on sediment rating method (interpolated).

unweighted." Figures 4.3 - 4.6 show time series of measured daily water discharge, measured daily sediment discharge, computed daily sediment discharge on the basis of either the "unweighted" method (a) (designated R) or the "interpolated" method (c) (designated I), and the relative error committed with respect to the actual daily measure ments. A number of different weighting schemes were investigated for method (b) and the results are bracketed by those from the interpolated (method (c)) and unweighted regression (method (a)). Moreover the implementation of many of these weighting schemes required much longer computations. Thus they will not be further discussed herein. In each case in these Figures 4.3 - 4.6, the data used for the predictions of daily sediment discharge are sampled at five day intervals. The overall performance of each of the methods are summarized in Table 4.3 and shown graphically in Figures 4.7 and 4.8.

In Table 4.3 and Figures 4.7 and 4.8, additional entries designated A are shown. These represent estimating the annual sediment yield by simply multiplying the arithmetic average daily sediment discharge by the number of days in the year. This is a method which does not require the daily water discharge data and becomes poorer as the number of samples decreases. However, none of the methods is clearly superior to the others although method (c) appears to be better for larger sampling intervals. Generally, increasing the sampling frequency from one every 30 days to one every 10 days (triple the sample rate) does not materially improve estimates of sediment

TABLE 4.3

Comparison of Methods for Estimating Average Daily Suspended Sediment Discharges (Tons/day)

$V_{ss}(A)$ = based on arithmetic average of sampled values

$V_{ss}(R)$ = based on logarithmic regression (see text for details)

$V_{ss}(I)$ = based on interpolated regression (see text for details)

Sampling Interval (days)	$V_{ss}(A)$	(error)	$V_{ss}(R)$	(error)	$V_{ss}(I)$	(error)
Susquehanna River (01570500)						
			1975			
1	10,893	0%	6298	-42%	10,893	0%
2	10,764	- 1%	6191	-43%	10,350	- 5%
5	9,904	- 9%	6921	-36%	9,040	-17%
10	16,675	+53%	9981	- 8%	10,020	- 8%
30	7,330	-33%	5229	-52%	7,300	-33%
			1976			
1	6162	0%	3729	-39%	6162	0%
2	6203	+ 1%	3758	-39%	6057	- 2%
5	5870	- 5%	3839	-38%	5099	-17%
10	7455	+21%	4086	-34%	5315	-14%
30	8863	+44%	3966	-36%	4217	-32%
Gila River (09474000)						
			1975			
1	4110	0%	803	-80%	4110	0%
2	3684	-10%	783	-81%	3650	-11%
5	4255	+ 4%	738	-82%	2276	-45%
10	2398	-42%	761	-81%	2051	-50%
30	1108	-73%	628	-85%	899	-78%
			1976			
1	5070	0%	244	-95%	5070	0%
2	4851	- 4%	237	-95%	6475	+28%
5	1631	-68%	189	-96%	3253	-36%
10	1244	-75%	204	-96%	2694	-47%
30	1426	-72%	186	-96%	2282	-55%

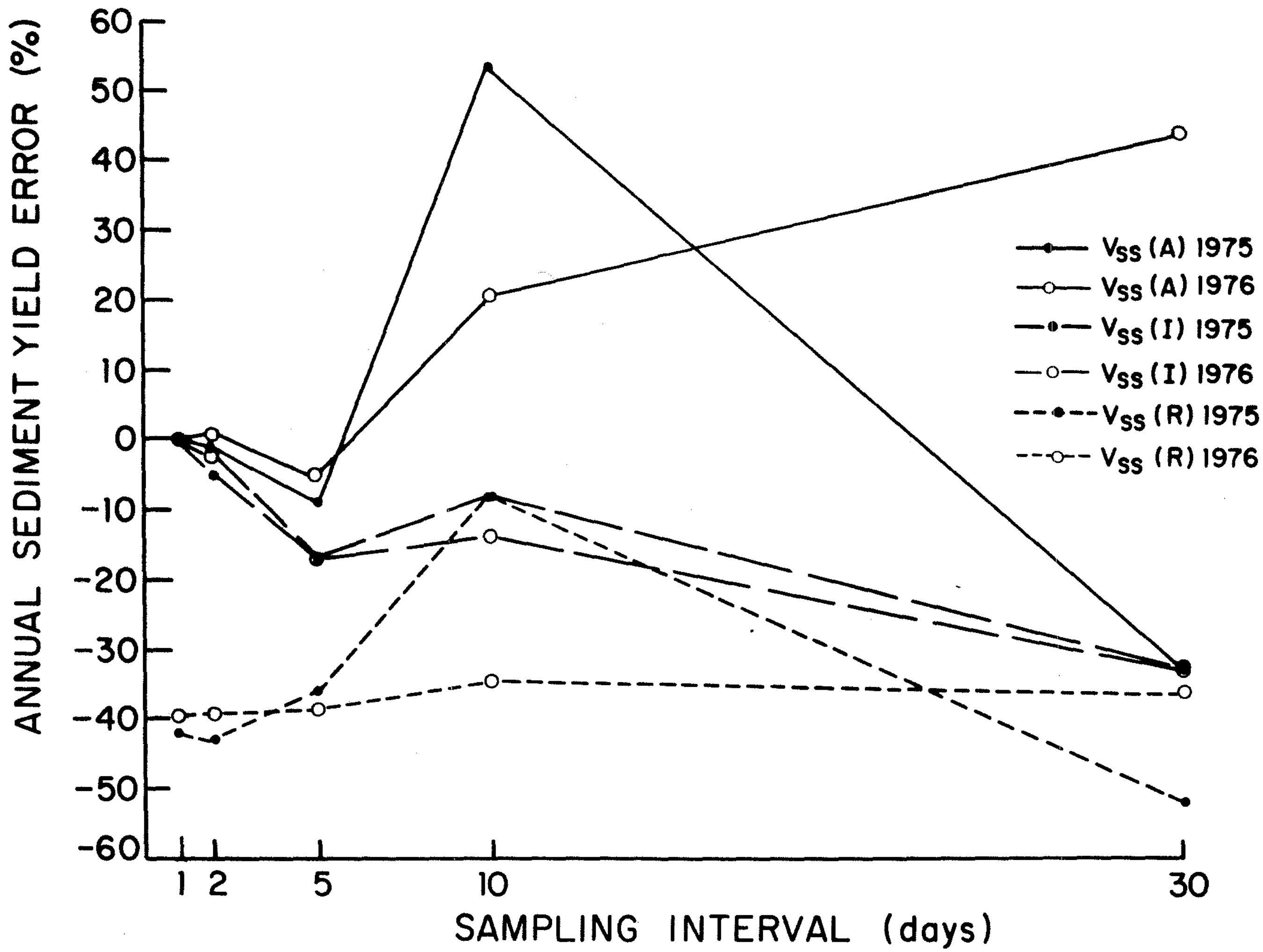


Figure 4.7 Comparison of several methods of sediment rating and their dependence on sample intervals for the Susquehanna River at Harrisburg (01570500).

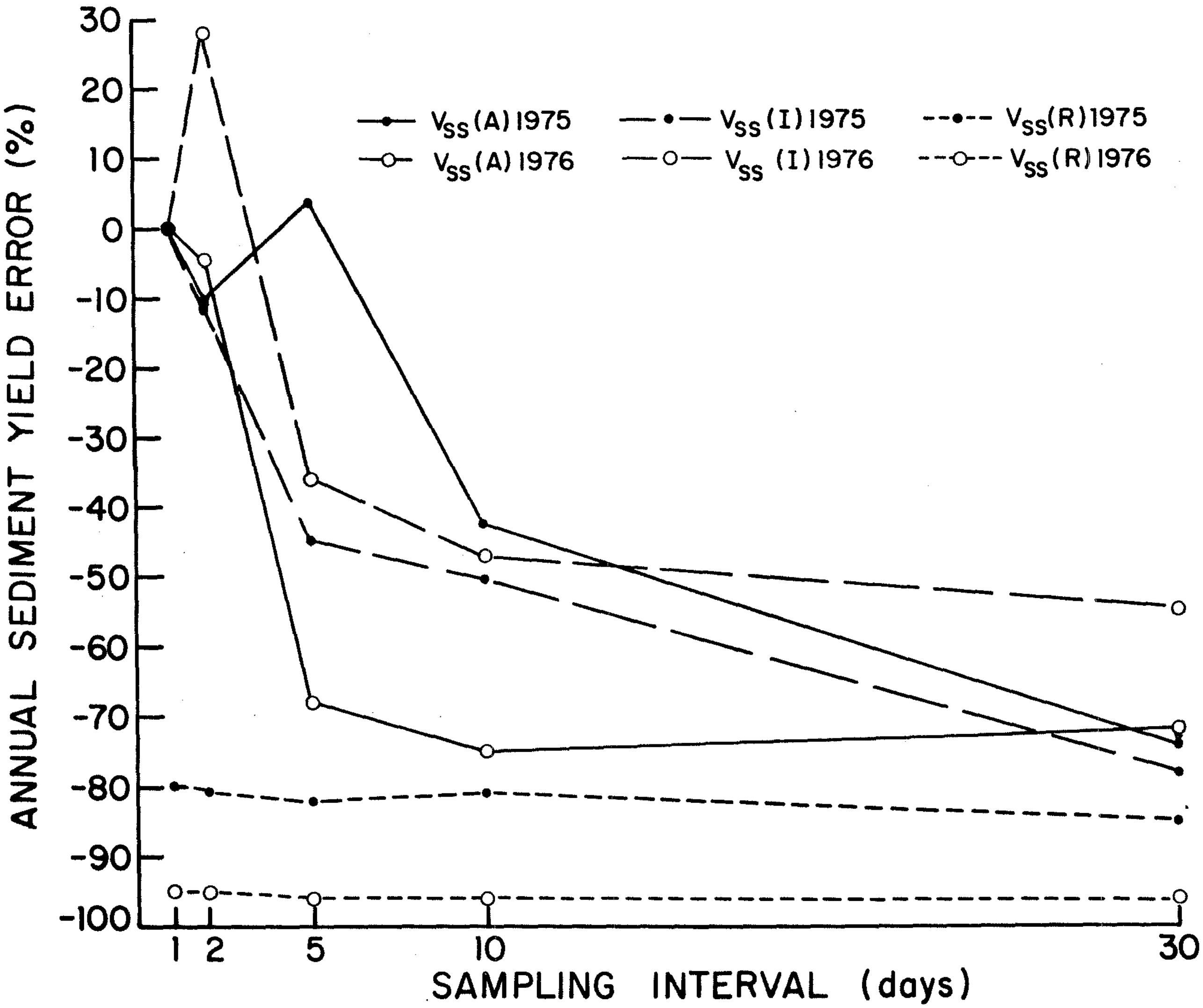


Figure 4.8 Comparison of several methods of sediment rating and their dependence on sample intervals for the Gila River at Kelvin (09474000).

yield. Even if sampling is done more frequently, no real improvement may occur until the sampling interval is about 5 days or less.

This analysis shows that (i) estimates can be made for annual sediment yield from the combination of isolated instantaneous sediment concentration measurements and daily water discharge measurements; (ii) these estimates do not improve significantly with increase in sampling frequency from every 30 days to every 5 or 10 days; (iii) the errors in the estimates appear to be generally negative (i.e., actual Q_{ss} is less than predicted), probably because of the logarithmic nature of the relationship; (iv) the order of magnitude of the errors in the estimate of the annual sediment yield is about 50% and (v) the accuracy of a particular estimate depends strongly on the hydrologic nature of the river.

CHAPTER 5

ERRORS IN SAMPLING SUSPENDED SEDIMENT IN RIVERS

A. Introduction

The problem of determining the transport rate of suspended sediment in a river from a few samples is a very difficult one. Because of the difficulties, determinations of transport rate are bound to involve errors.

Errors in sampling can be put into two classes: 1) those arising from the unsteadiness of rivers, and 2) those resulting from imperfections in instrumentation and sampling procedures. Some but not all errors in these two classses are discussed below.

B. Effect of Unsteadiness

The extent of unsteadiness is illustrated in tests made in connection with the design of suspended load samplers in which the effect of the time of sampling on sediment concentration was observed (Inter-Agency Committee on Water Resources 1941, p. 28). Successive samples were withdrawn from a laboratory flume with a fixed sharp-edged tube sampler for periods of 20 sec. The concentration in these samples varied as much as 37 percent from the mean. When the sampling period was increased to one minute the concentrations varied as much as 10.5 percent from the mean. In order to withdraw a sample that effecively reflected the true mean concentration a sampling period of 10 minutes was used. The grain size of the sediment in these tests was not given.

Vanoni (1946) withdrew 1-liter samples from a point 0.1 ft above the bottom of a flow approximately 0.5 ft deep. The velocity at the level of the sampler and in the sampler inlet was 3.19 ft per sec and the sediment was quartz sand with a sieve diameter of 0.147 mm. The time to withdraw a liter sample was 25 sec and the length of the filament withdrawn was approximately 80 ft. Despite these rather long sampling times, the concentration of sediment in the individual samples varied from +6 percent to -5 percent of the mean.

The flows in the above tests were statistically steady so that the mean velocity and discharge were steady and fluctuations were due to turbulence alone. Flows in a river are seldom steady so that fluctuations in discharge will also cause variations in concentration. For this reason the variations in the above cases are probably less than may be expected in rivers.

Examples of the fluctuation of concentration in 20 consecutive depth-integrated samples at a vertical are shown in Fig. 5.1, taken from Guy (1970). The Middle Loup River, in which the data of Figure 5.1 were collected, is a small river, with a bed of medium sand. The variation in concentration in the flow over the dune bed is seen to be much larger than that for the flat bed flow. This is to be expected because of the change in flow conditions as the dunes move past the site of the sampling vertical (Guy (1970)).

The procedure in sampling suspended load in rivers is to take one

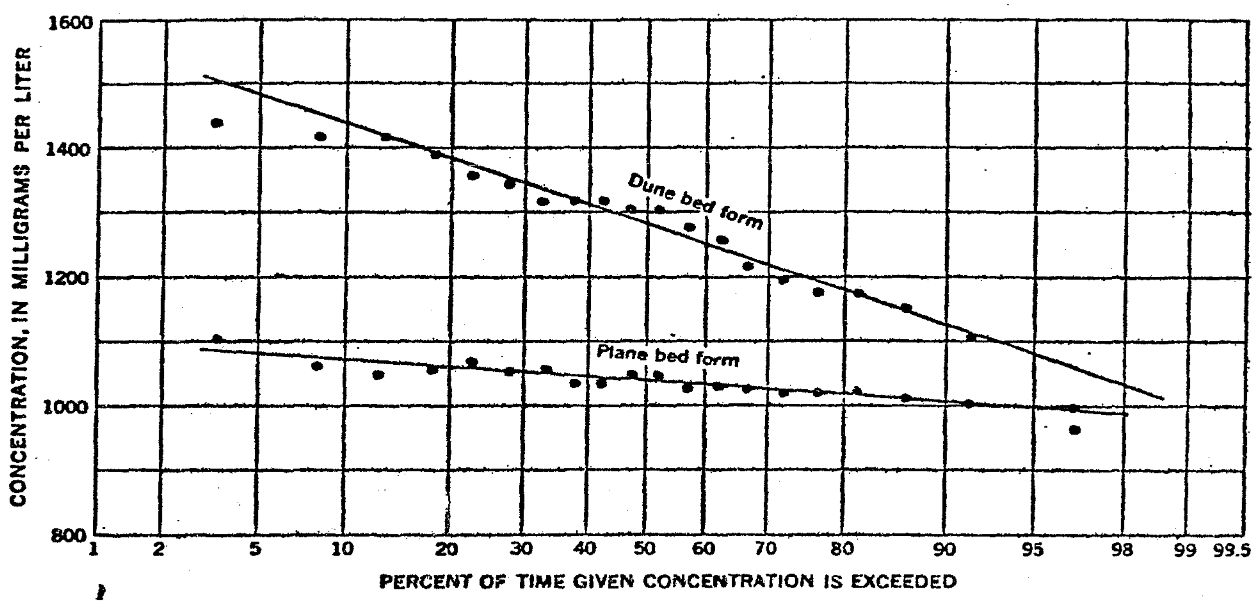


Figure 5.1 Frequency distributions of consecutive sampled concentrations at single verticals of the Middle Loup at Dunning, Nebraska, from Guy, 1970.

depth-integrated sample at each of several verticals in a cross section. Except for deep rivers, this involves two transits of the sampler, from surface to bed and return. This excursion of the sampler usually takes less than a minute so that some averaging of the short duration fluctuations in concentration is done in the two passes of the sampler. However, fluctuations with a longer time than the sampling time are not averaged.

Taking a single sample from a population such as shown in Figure 5.1 for the dune bed can result in large errors. Suspended sediment with particle sizes finer than 0.062 mm in the Middle Loup River ranged from 9 to 56 percent by weight of the total measured concentration. This fines fraction is less than in many rivers. The fine sediments tend to be uniformly distributed over depth, so that the concentration in these sizes would be expected to show less short term fluctuations than for sands. Thus the measured short-term fluctuations in <u>total</u> suspended sediment concentrations in the Middle Loup River are larger than those that would probably obtain in rivers transporting a larger percentage of fine sediments.

The sampling error could be reduced by taking several samples at each vertical. However, the improvement in the estimate of concentration occurs slowly with the number of samples and benefits from the added samples may not justify the increase in costs.

In summary, it is clear that because of unsteadiness in rivers errors of unknown magnitude arise in sediment concentrations determined from single depth-integrated samples at verticals. It would be of interest to users of sediment data to know the confidence limits of data used in planning engineering works. A start could be made in determining these confidence limits by collecting data such as those in Figure 5.1 for a few representative rivers such as the six distributed river systems used in this study.

Methods for estimating the confidence limits of mean concentration at a station determined from depth-integrated samples at several verticals were presented by Guy and Norman (1970). Results of such procedures are not published routinely, indicating that such procedures are not applied regularly.

C. Effect of Sampler Characteristics

Much effort in the United States has gone into developing samplers for sampling the suspended sediment of streams. Two general types are in use: the depth-integrating and the point-integrating types. The depth-integrating sampler (Figure 5.2) takes in a sample of water and its complement of sediment as it transits the flow from water surface to bed and return. The point-integrating sampler is essentially the same as the depth-integrating type, except that it is equipped with a valve mechanism that allows the operator to open or close the sampling nozzle. While the sampler is being positioned, the nozzle is kept closed, opened long enough to take a sample, and then closed before it is brought to the surface to retrieve the sample. It can also operate as a depth-integrating sampler with the valve in the open position. It is especially useful in deep streams where the

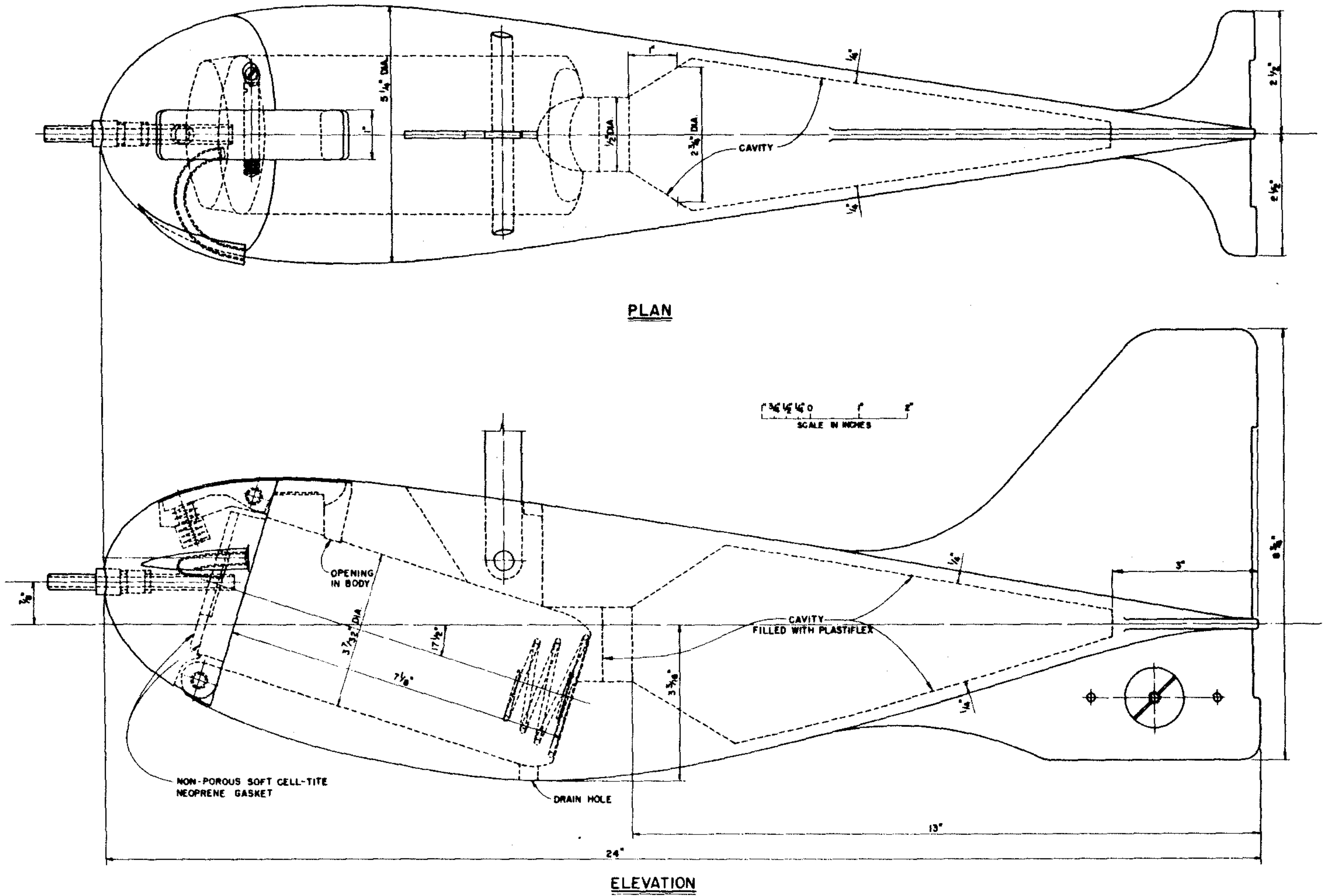


Figure 5.2 Depth-integrated suspended sediment sampler, US D-49.

volume of the sample collected while transiting the stream from surface to bed and return exceeds the volume of the sample container. In such cases the point integrating sampler can be used to take samples in steps over parts of the flow depths until the desired coverage is made.

As part of this study, a review was made of possible errors due to operation of the depth-integrating suspended sediment sampler (US D-49). The discussion and analysis is given in the Appendix. In brief, the possible errors due to operation of the sampler itself are estimated to be about 2% or less, based on calculations for a particular case where errors might be expected to be larger than average. These values are very small compared to other sources of error, such as river unsteadiness and the unmeasured portion of the transport near the bed below the reach of the suspended sediment sampler. Such low errors are the result of the excellent design of the sampler which dynamically achieves a sample-intake velocity equal to the stream velocity at the sampling point.

D. Effect of Variable Transit Rate of the Sampler

There are a number of problems which arise while taking samples and which contribute to errors. One such problem is to maintain uniform vertical transit rate of the samplers which is required if a proper sample is to be obtained.

The present practice is to depend on the operator to keep the transit rate constant as the sampler is hand cranked down into the flow and returned. The largest departure from constant velocity is at the bottom of the stream where the motion should be reversed instantaneously. The sampler can dip into the bed. It also generally is slowed down in the vicinity of the direction reversal and therefore takes in an excessive amount of sample near the bed where the sediment concentrations are relatively high, and this tends to give too large a measured concentration. This problem is amplified in high velocity flows where the sampler drifts downstream. The magnitudes of errors due to variable transit rate is not known.

E. Estimating Unmeasured Sediment Discharge

Suspended sediment samplers measure the suspended sediment only from a point approximately 0.3 ft above the bed up to the water surface. Sediment suspended in the thin layer near the bed and the bed load moving on or very near the bed are usually estimated. This sediment is called the unmeasured load of the stream, and the discharge corresponding to this load is called the unmeasured sediment discharge.

The most common method of determining the unmeasured sediment discharge is by formulas. The most reliable of these is known as the Modified Einstein Method (Colby and Hubbell, 1961). However, this method requires more field data than is usually collected and therefore is not routinely applied. A simplified variant of the above method which only requires measurements of mean velocity, stream width, mean stream depth, the suspended sediment concentration and the concentration of bed sediment in the depth-integrated samples, has been proposed by Colby (1957). Errors in estimates of unmeasured sediment discharge based on bed-load formulas may be large since results of such formulas are known to vary appreciably even for comparatively simple laboratory flows. Due to the uncertainties in estimates based on formulas, and for reasons of economy, the unmeasured sediment discharge is sometimes taken simply as a fraction of the measured suspended sediment discharge. Such fractions are usually based on experience and may involve substantial errors.

The unmeasured load involves only bed sediment since the wash load is measured adequately with the depth-integrating samplers. The errors in total sediment discharge resulting from errors in estimating unmeasured sediment discharge depend in part on the ratios of the discharge of bed sediment to discharge of wash load. If this ratio is small, the errors in total sediment discharge will be insensitive to errors in estimates of unmeasured sediment discharge.

Results from studies of the Colorado River by the Bureau of Reclamation (1958) give an example of the relative magnitude of the unmeasured sediment discharge which was estimated by the Modified Einstein Method. During the study the depth of the river ranged from 4.6 ft to 11 ft, the median size of the bed sediment was 0.33 mm and the suspended silt and clay was 14% by weight of the measured suspended load (which is much smaller than in most rivers in the United States). The unmeasured sediment discharge ranged from 30% to 56% of the total sediment discharge and from 34% to 60% of the total sand discharge. Thus, in this case the errors in the total sediment discharge would range from 30% to 56% of the errors in estimating unmeasured sediment discharge.

F. Summary

1. The effect of unsteadiness in streams on the overall estimate of sediment discharge appears to be larger than any of the other errors discussed in this report. Unsteadiness has been observed in the laboratory and in streams. In order to estimate errors in sampling resulting from fluctuations in concentration and sediment, transport rate data of the kind shown in Figure 5.1 for the Middle Loup River are needed for at least a number of typical rivers.

2. The hydrodynamics of the sediment samplers developed jointly by United States Federal agencies cause the intake velocity to match the local stream velocity, thus limiting concentration sampling errors to a few percent. According to the analysis in the Appendix, even the hydrodynamic tilting of the samplers and the inclination of the approach velocity vector relative to the sample cause only +2% error or less in typical cases.

3. However, the unavoidable variability of sampler transit rate in the vertical is recognized as a source of error in sampling. No estimate of errors from this source have been made. (The analysis in the Appendix presumes uniform transit rates of the sampler in the vertical.) Control of this error requires skill and care by the operator of the sampler.

4. The errors in estimates of the discharge of unmeasured load when determined by bed load formulas can be substantial. Errors in

estimates based on a percentage of the measured suspended load are also expected to be large. The most reliable estimates of unmeasured sediment discharge are those obtained with the Modified Einstein Method. But this method required field measurements not made routinely so estimates using this method are not usually made.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

1. It is possible to obtain a fair to good estimate of sediment yield from NASQAN sediment data when used in combination with daily water discharge data. The estimate does not improve materially with a moderate increase in sampling frequency (such as from 30 to 10 days).

2. In answering sedimentation questions, it is recommended that all available suspended sediment data be used rather than just NASQAN data.

3. By themselves, the monthly NASQAN sediment data are of much less usefulness than when used in combination with the NASQAN daily water discharge measurements.

4. The data bank may be improved by using automatic data checking. This automatic checking could eliminate most of the errors we encountered (such as data in wrong columns, repeated entries, impossible values, etc.). The level of errors we encountered in available data is too high to allow for direct use without screening by the user.

5. The spatial distribution of NASQAN stations is reasonable but necessarily judgemental. In cases when NASQAN is the only source of data, the general areal distribution does not meet needs for site specific sediment problems.

6. Temporal variations of sediment data contain much higher frequencies than just monthly variations. Thus, monthly samples would be heavily aliased. Any analysis which depends on the time sequencing of data (such as trend analysis) is made difficult.

7. Supplemental measurements of sediment transport during flood events would improve sediment rating curves by improving the definition of the important upper part of the curve.

8. Errors in measurement and the sediment sampling technique have been examined in detail. It was found that these errors are manageable and at present are smaller than other factors such as sampling frequency.

9. The technique of suspended sediment rating, while a valuable tool in the interpretation of sediment data, is an imprecise concept particularly on streams with heavy sediment loads and shifting bedforms.

10. Increased understanding of the mechanics of alluvial streams and sediment transport can be achieved on selected stations with bed sediment samples, cross sectional surveys, and size analyses of sediment samples.

11. Future research would be worthwhile to relate sediment data to water quality NASQAN data, to assist in the interpretation of the latter.

12. The characteristics of temporal fluctuations in the other NASQAN data should be determined in order to assess the adequacy of monthly or quarterly sampling intervals.

13. The entire sediment sampling program of the U.S. Geological Survey should be examined as a whole rather than NASQAN alone.

APPENDIX

PERFORMANCE OF DEPTH-INTEGRATING SUSPENDED SEDIMENT SAMPLERS

A. Effect of Relative Sampling Rate.

The relative sampling rate is defined as the ratio of the velocity v_s at the inlet to the sampler nozzle to the undisturbed stream velocity, u at the level of the nozzle. Experimental investigations showed that when the relative sampling rate was maintained at unity (normal sampling rate) the most representative samples were obtained and that departures from unity caused a deviation from the true concentration. The value of relative sampling rate and its departure from unity has been taken as a criterion for judging the quality of a sample.

Figure A.1 is a graph (Inter-Agency Committee on Water Resources, 1952) showing errors in concentration of 0.45 mm sand in samples taken at different sampling rates at a point where the velocity is 5 ft/sec. The measurements were made in three different laboratory flows with mean sediment concentrations and temperatures as shown in the graph. The sampler tube, which was directed into the flow, was 1/4 inch in diameter, had a sharp edge, and was connected to a tube which conveyed the sample out of the channel at right angle to the flow. Figure A.1 shows that sampling ratios less than unity (intake velocity too low) result in positive errors (sample concentrations too high); conversely, for intake velocity too high, the measured concentration

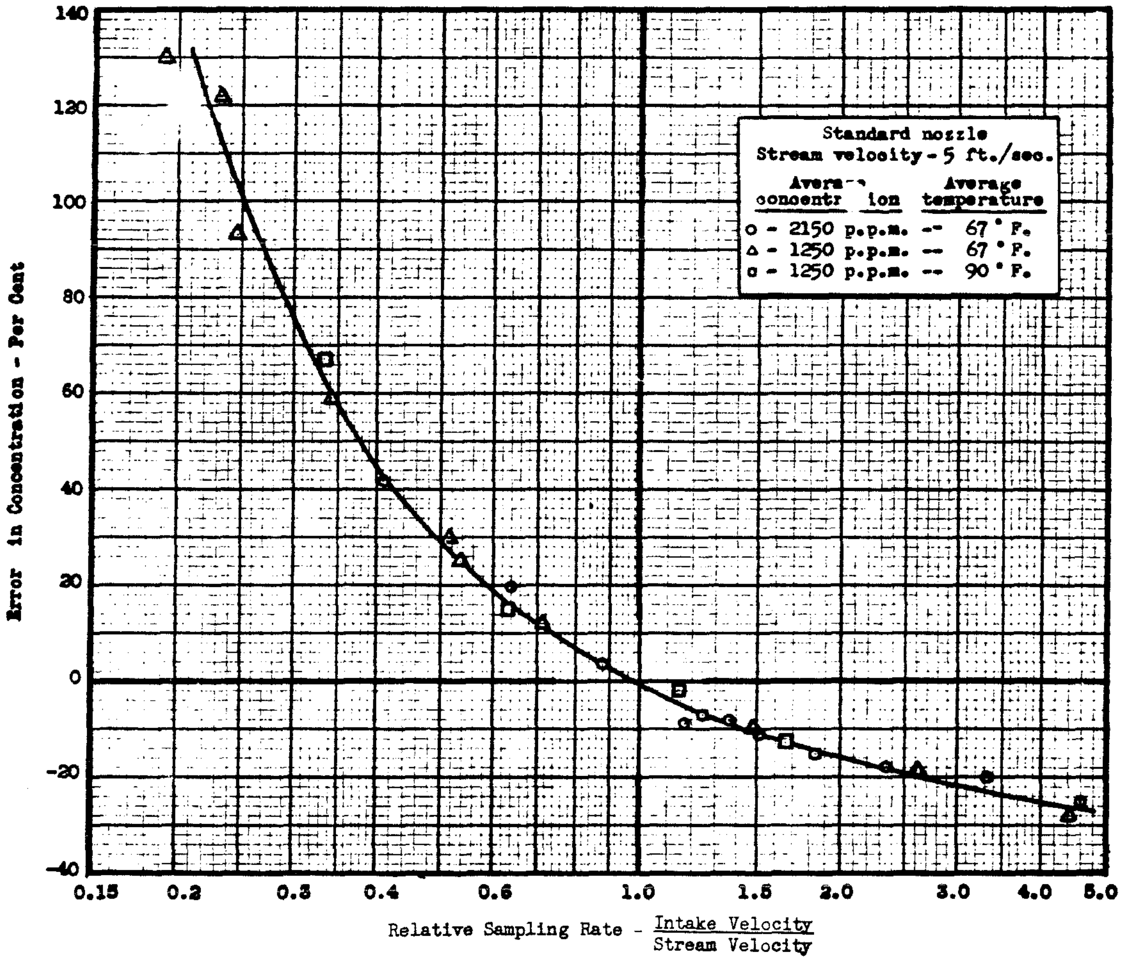


Figure A.1 Effect of sampling rate on sediment concentration -- 0.45 mm. sediment. (From Inter-Agency Committee on Water Resources, 1952) (1/4 diameter sharp edged sampler aligned with the flow.)

is too low. Figure A.1 also shows that errors resulting from deficiencies in sampling rate increase faster than those caused by excesses in sampling rate. The sampling errors due to deviations from the sampling ratio of unity increase with sediment size as shown by Figure A.2 taken from (Inter-Agency Committee on Water Resources, 1952).

B. <u>Effect of Sampler Alignment</u>

The effect of orienting the sampler nozzle away from its alignment with the flow, its normal alignment, has been studied in the laboratory with the same apparatus and nozzle used to develop the data of Figures A.1 and A.2. The results of such studies (taken from Inter-Agency Committee on Water Resources, 1941) are shown in Figure A.3. Errors in sample concentration are shown as a function of relative sampling rate for normal alignment and deviations of 20° and 30° from the normal. Tests were also made with the sampler deviating 10° from the normal alignment. The results for 10° deviations are not shown on Figure A.3 because they did not differ from those with the normal orientation. Even the errors for a deviation angle of 20° differ only slightly from those for the normal settings.

C. <u>US Depth-Integrating Samplers</u>

The US D-49 depth-integrating sampler is typical of depth integrating samplers. A drawing of the US D-49 is shown in Figure 5.2.

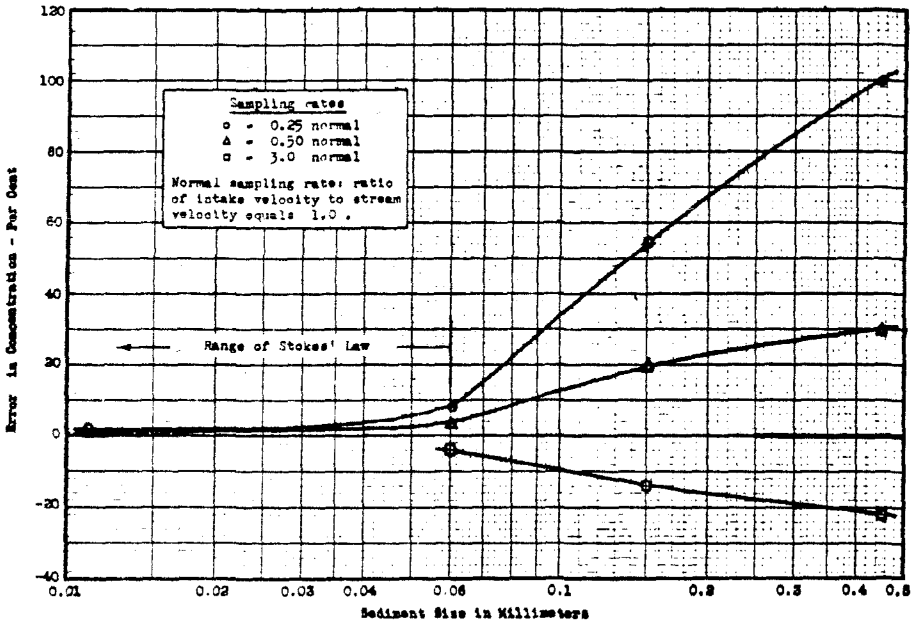


Figure A.2 Relation of sediment size and sampling rate to errors in sediment concentration. (From Inter-Agency Committee on Water Resources, 1941)

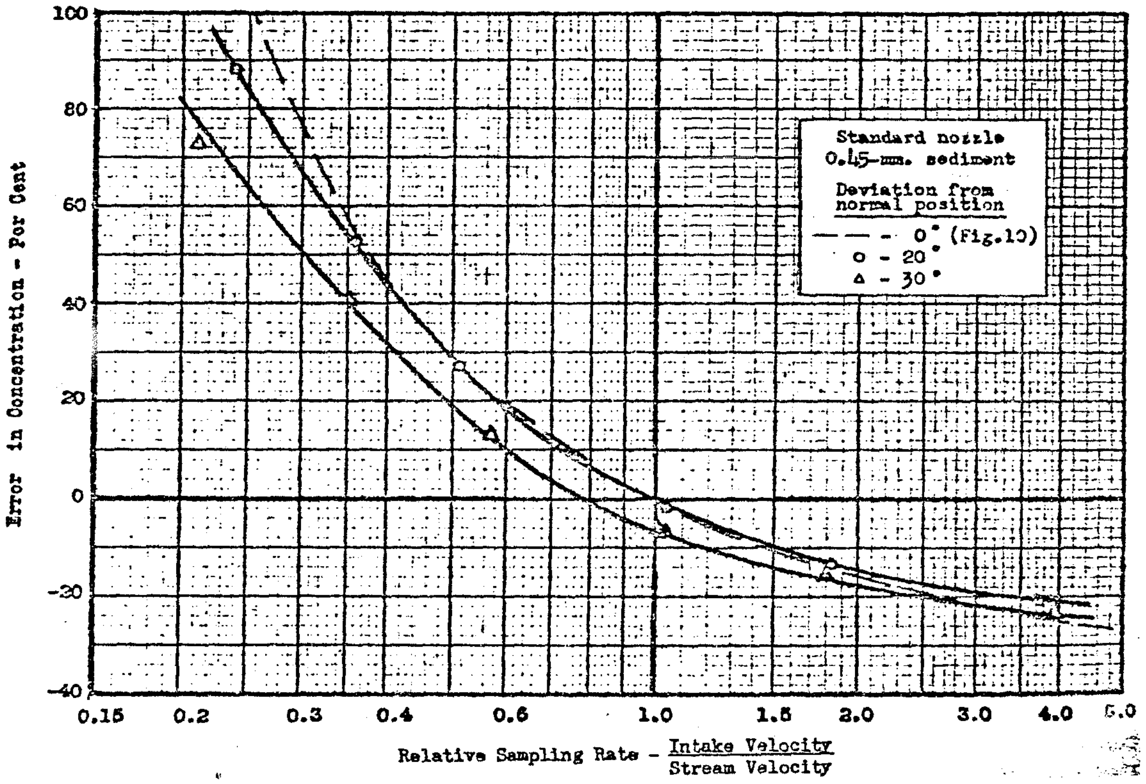
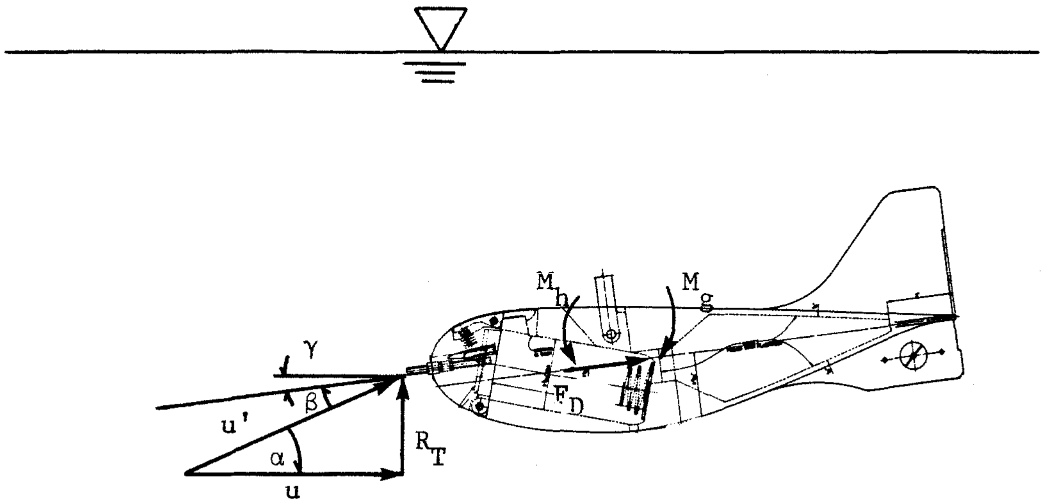


Figure A.3 Effect of small deviations from normal nozzle orientation on errors in sediment concentration. (From Inter-Agency Committee on Water Resources, 1941)

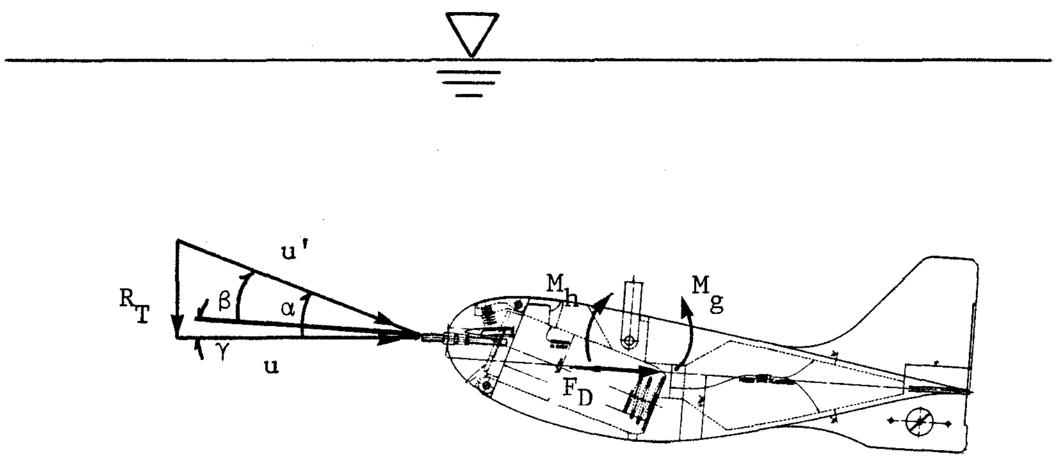
The sampler is designed to give a relative sampling ratio of unity while held stationary and aligned with the flow. The air in the sample bottle escapes from the sampler as it is displaced by the fluid entering the sampler. By properly locating the exhaust port the difference in pressure head between the nozzle tip and the port can be made to equal the head loss in the inlet passages of the sampler at the correct sampling flow rate. Both this head difference and head loss depend in the same way on the local stream velocity. Therefore once the relative sampling ratio is adjusted to unity for one flow velocity it will obtain for all others. From Figure 5.2 it will be noted that the air exhaust port is located on the sampler nose near the maximum diameter where the pressure has been reduced below that at the inlet due to the increase in velocity over the sampler. Note that on the US D-49 there is a stop which prevents the sampler from pitching downward without also rotating the vertical support bar.

When the depth-integrating sampler is transiting a flow either upward or downward on a cable, the motion of the water relative to the sampler nozzle will be u', the vector sum of the local stream velocity, u, and the transit rate, R_T, of the sampler. This is shown in the diagrams of Figure A.4. The resultant velocity u' is inclined to the stream velocity with an angle $\alpha = \tan^{-1} R_T/u$. The pitch of the sampler is γ which is less than α, and β is the angle of u' relative to the sampler.

An attempt is made here to estimate roughly the forces and moments in the US D-49 sampler. These forces and moments are then



a) Downward Motion



b) Upward Motion

Figure A.4 Forces on Suspended Sediment Sampler While Moving Vertically applied to the sampler in an attempt to estimate roughly the pitch angle β during sampling. The sampler is acted upon by a drag force F_D, a gravity moment, M_g and an hydrodynamic moment, M_h.

The gravity moment M_g was measured while the sampler with sample container was suspended in water. For upward pitch and for unrestrained downward pitch,

$$M_g = 0.10\,\gamma \quad \begin{array}{l}(\text{Mg in foot-pounds})\\ (\gamma \text{ in degrees})\end{array} \qquad (1)$$

For downward pitch when the support bar is hard against the stop,

$$M_g = 0.63\,\gamma \quad \begin{array}{l}(\text{Mg in foot-pounds})\\ (\gamma \text{ in degrees})\end{array} \qquad (2)$$

The submerged weight of the sampler was 55 lbs. The hydrodynamic moment, M_h, and the drag, F_D, can be expressed in terms of coefficients C_M and C_D, respectively.

$$F_D = C_D A \frac{1}{2} \rho u'^2 \qquad (3)$$

$$M_h = C_M D A \frac{1}{2} \rho u'^2 \qquad (4)$$

In equations (3) and (4), C_D = drag coefficient, C_M = moment coefficient, A = maximum area of cross section of the sampler, ρ = density of the water, u' is the water velocity relative to the sampler and D is the maximum diameter of the sampler body.

Values of C_D and M_h are not known. In order to proceed with the calculation values the coefficients have been selected from tests of projectiles in a water tunnel. The values selected are $C_D = 0.15$ and $C_M = 0.01\beta$ which are for a projectile with an overall length equal to 7 diameters, a spherical head, a cylindrical center section 3.3 diameters long and a gently tapering tail section 3.2 diameters long with tailfins.

Taking moments about the support pin (Figure A.4) gives,

$$M_h + F_D a - M_g = 0 \tag{5}$$

for downward motion, and

$$-M_h + F_D a + M_g = 0 \tag{6}$$

for upward motion, if a is the moment arm of the drag force F_D. Another relation is

$$\beta + \gamma = \alpha \tag{7}$$

Solution of these equations with D = 5.25 in. and a = 1.25 in. and extreme values of $R_T = 0.4$ u and u = 5 ft/sec gives $\gamma = 3^\circ$ when the sampler is not restrained against pitching by the support bar. Although this analysis is very rough the results agree with observations (Inter-Agency Committee on Water Resources, 1952) that the sampler tilts only a few degrees from the horizontal as it is moving over the depth of a flow.

Because depth-integrating samplers pitch very little as they are moved vertically in a flow, the angle β between the axis of the inlet nozzle and the vector velocity u' is only slightly less than α (see Figure A.4). This means that the sampler is always inclined to the velocity u' and that according to Figure A.3 there will be errors in the samples taken which depend on the inclination angle β and the relative sampling rate.

The sampling rate in a depth integrating sampler is determined by the shape of the sampler head. Samplers are designed to give a relative intake ratio of unity when held in a fixed position and aligned with the flow. Figure A.5 shows the effect on the relative sampling rate of the US D-43 sampler on its inclination to the flow. Figure A.5b shows the effect of inclination on the intake ratio which is defined as the ratio of intake velocity to the component of the approach velocity parallel to the nozzle axis. The relative sampling rate varies with the flow velocity and has different values for upward and downward tilt. Because the heads of the US D-43 and the US D-49 sampler are similar, the data in Figure A.5 should apply to both samplers. To estimate the error in the sample concentration one can read from Figure A.5 the values of the relative sampling rate for a given inclination angle and velocity. Then the errors in concentration can be read from a graph similar to Figure A.3 prepared for the sampler and the desired sediment size and flow velocity.

In using Figure A.5 for downward transit read the upward-tilt

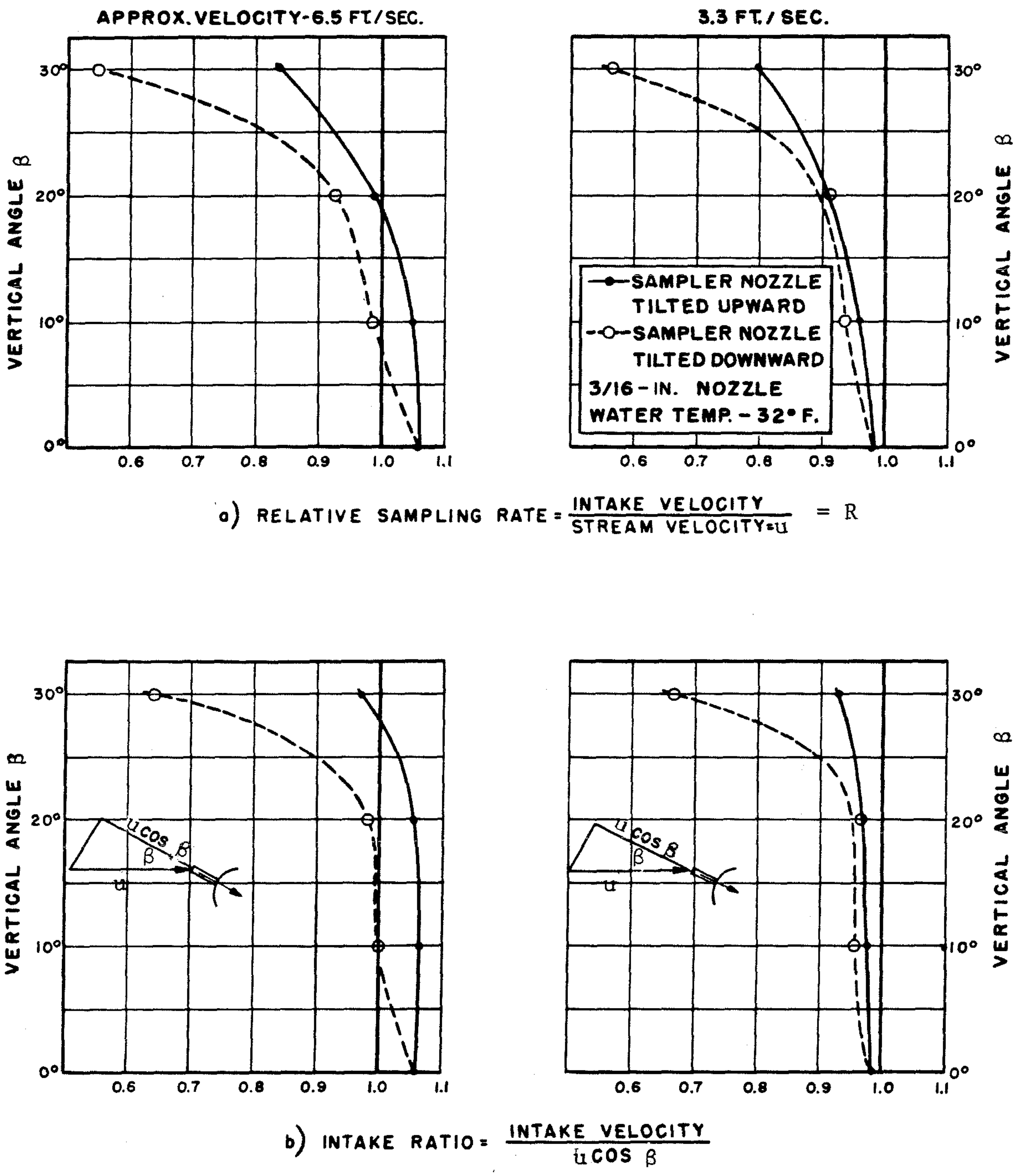


Figure A.5 Effect of small deviations from normal nozzle orientation on intake characteristics of US D-43 sampler. (From Inter-Agency Committee on Water Resources, 1952) curve and for upward transit read the downward-tilt curve, based on the direction of the nozzle relative to the velocity vector u' for each case.

When the sampler is moving up or down, the velocity u in Figure A.5 is equivalent to u'. The angle β between the velocity u and the sampler nozzle is slightly less than α and can be estimated by applying Equations 5, 6 and 7 with the estimated drag and moment coefficients. The ratio of intake velocity to local stream velocity u_s/u in Figure A.5 becomes,

$$R = \frac{u_s}{u \cos \gamma} = \text{intake ratio} \qquad (8)$$

The intake ratio R can be read from Figure A.5 as a function of β, the velocity and the direction of transit.

Calculations were made for the angle β based on equations 5 and 6 and the estimated values of C_D and C_M. The calculations are for two flow velocities u, of 3.3 ft/sec and 6.5 ft/sec and two transit rates $R_T = 0.3$ u and $R_T = 0.4$ u. The results of these calculations are shown in Table A.1.

The angle of attack γ of the sampler varies from less than one degree to six degrees for the conditions of velocity and transit rate assumed in the calculations. The angle β between the centerline of the inlet tube of the sampler and the relative velocity u' differs from α, the angle between u and u', by the angle γ as shown in Figure A.4.

The relative sampling rates for the D-43 sampler were read from Figure A.5a assuming that the vertical angle (ordinate of Figure A.5a)

TABLE A.1

Calculated Values of Angles β and γ and Relative Sampling Rate for US D-43 Sampler Based on Equations 5 and 6 and Figure 7

Velocity $\bar{u}$ ft/sec	$\frac{R_T}{u}$	Transit direction	Angle β deg.	Angle γ deg.	Relative* Sampling Rate
6.5	0.3	down	12.1	4.6	1.04
6.5	0.4	"	15.8	6.0	1.02
3.3	0.3	"	15.3	1.4	0.94
3.3	0.4	"	19.9	1.9	0.91
6.5	0.3	up	13.7	3.0	0.98
6.5	0.4	"	17.5	4.3	0.95
3.3	0.3	"	15.8	0.9	0.92
3.3	0.4	"	20.4	1.4	0.89

*From Figure A.5.

is equal to β. Figure A.3 gives data on concentration errors for a simple tube sampler as a function of the angle of the sampler relative to the velocity vector and relative sampling rate. These data do not apply to the US D-43 sampler because of the difference in flow geometry between the simple tube and the US D-43 sampler. However, Figure A.3 is used here to obtain a rough indication of errors. The angles β in Table A.1 vary from 12° to 20° and the relative sampling rates vary from 0.9 to 1.04. Errors in concentration were read from Figure A.3 for three sets of values of β and sampling rate. These are shown in the following table.

β degrees	Sampling rate R	% error in concentration
10	1.04	-2
15	0.9	-1
20	0.9	-4

The data in Figure A.3 are for 0.45 mm sediment which is much coarser than suspended sediments found in most streams. The errors in concentration of sediments decreases as the sediments become finer (Figure A.2) so that the errors given above are higher than normal. Thus if the calculations of Table A.1 were for finer sediment normally found in streams the sampling errors would be smaller.

The velocity, u in a stream varies from zero at the bed to a maximum at or near the surface. Let us assume that the two velocities assumed in the calculations for Table A.1 are mean velocities at a vertical. Then the velocities near the bed will be less than the mean velocities making the angle α and hence β larger than shown in Table A.1. This would tend to increase the deviation of the sampling rate from unity and to increase the sampling error. Since the concentration is largest near the bed errors in these concentrations will have greater effect on the over-all error than those in the upper regions of the flow.

The results of the above calculations are based on roughly estimated values of moment and drag coefficient and the assumption that the sampler is symmetrical about a horizontal plane. Also the data on Figure A.3 taken with a sharp edged nozzle do not apply to the nozzles on the depth integrating samplers. Therefore these results are not conclusive. But the above calculations provide an example of how the performance of a sampler might be predicted.

D. Fields Test of Samplers

A comprehensive set of tests of depth-integrating samplers was carried out on the Colorado River near Grand Canyon, Arizona by the U.S. Geological Survey (Inter-Agency Committee on Water Resources, 1951). Samples were taken at one vertical during a 10-day period in which the flow depth at the vertical was between 22 ft and 26 ft and the mean velocity ranged from 7.1 to 8.2 ft per sec. The concentration of suspended sediment was between 3000 to 4800 ppm and approximately 30% of the sediment was finer than 0.0625 mm, 20% was between 0.0625 mm and 0.125 mm in size and approximately 50% was coarser than 0.125 mm.

The intake ratios (relative sampling rates) and concentration ratios for the samples taken are shown in Table A.2. The intake ratio is the ratio between the mean velocity in the sampler nozzle during sampling and the mean velocity over the portion of the vertical that is sampled. The concentration ratio is the concentration in the depth-integrated samples divided by the concentration calculated from point-integrated samples, point-velocity measurements and sampling times. Most of the depth-integrated samples were taken with the US P-46 and US P-46A point samplers. Only a few were taken with the US D-43 depth integrating sampler because in order to cover the large depth the vertical transit rate had to exceed the maximum recommended values. For this reason the data for the US D-43 sampler are viewed as examples of performance under conditions which the sampler should not be used.

Because of the high velocity and stream depth at the Grand Canyon site during the sampling tests, difficult problems were encountered. Corrections had to be made for downstream drift of the current meter and sampler, and errors resulted because high transit rates were often necessary. Because of these unusual conditions considerable judgement was needed by those participating in the tests to eliminate faulty data and to judge what data were acceptable. The authors of the report judged that in the Colorado River tests the US P-46 and US P-46S samplers when used in the depth integrating mode had a relative

TABLE A.2

SUMMARY OF DATA FOR DEPTH-INTEGRATED SAMPLES

(Inter-Agency Committee on Water Resources, 1951)

OPERATION	No. SAMPLES	AVERAGE RATIOS	
		INTAKE*	CONCENTRATION
Samples depth-integrated with P-46 and P-46S	128	0.98	1.00
Integrated downward	52	1.04	0.99
Integrated upward	66	0.94	1.01
Integrated round trip	10	1.00	1.06
Integrated over full depth	63	0.99	1.00
Integrated downward	24	1.07	1.00
Integrated upward	39	0.94	1.00
Integrated over partial depth	65	0.97	1.01
Integrated downward	28	1.01	0.98
Integrated upward	27	0.92	1.02
Integrated round trip	10	1.00	1.06
Samples depth-integrated with P-46	72	0.99	1.03
Integrated downward	31	1.04	0.99
Integrated upward	31	0.93	1.05
Integrated round trip	10	1.00	1.06
Integrated over full depth	26	1.02	1.03
Integrated downward	13	1.10	0.98
Integrated upward	13	0.94	1.07
Integrated over partial depth	46	0.97	1.03
Integrated downward	18	1.01	1.00
Integrated upward	18	0.93	1.04
Integrated round trip	10	1.00	1.06
Samples depth-integrated with P-46S, 3/16-in. noz.	28	0.95	0.97
Integrated downward	10	0.97	0.97
Integrated upward	18	0.94	0.97
Integrated over full depth	19	0.95	0.99
Integrated downward	5	0.95	1.02
Integrated upward	14	0.94	0.98
Integrated over partial depth	9	0.96	0.94
Integrated downward	5	0.99	0.93
Integrated upward	4	0.92	0.95
Samples depth-integrated with P-46S, 1/8-in. noz.	28	0.99	0.98
Integrated downward	11	1.08	1.00
Integrated upward	17	0.93	0.97
Integrated over full depth	18	1.01	0.98
Integrated downward	6	1.12	1.04
Integrated upward	12	0.95	0.96
Integrated over partial depth	10	0.95	0.97
Integrated downward	5	1.04	0.95
Integrated upward	5	0.88	0.99
Samples depth-integrated with D-43, 1/8-in. noz.	12	1.44	0.86
Integrated over full depth	9	1.50	0.84
Integrated over partial depth	3	1.25	0.91

* Computed on basis of horizontal stream velocity.

sampling rate of 1.09 when integrating downward and 0.94 when integrating upward. The concentration ratios for these samplers are 1.00 for downward integration and 1.03 for upward integration.

The relative sampling rates shown in Table A.1 are higher on the upward transit than on the downward transit and in this regard disagree with those obtained in the Colorado River tests. This disagreement is probably due to the rough approximations of the hydrodynamic factors used in the calculations.

The concentration ratios obtained by calculation ranged from 0.98 to 1.02 and compare favorably with 1.00 to 1.03 obtained in the river tests. This may be fortuitous since the calculations were based on M_g values for the US D-49 sampler. The data in Figure A.5 are for the US D-43 sampler fixed in a flow while the Colorado River tests were with the US P-46 samplers. The results of the calculation in Table 5.1, at best, must be taken as an indication and not quantitatively.

E. Summary

1. Samplers developed by the Federal Agencies of the United States tend to tilt as they are moved vertically in a stream. The tilt angle can be estimated based on hydrodynamic drag and moment coefficients which have not been measured but have been estimated for the US D-49 sampler. The tilt angle of the sampler was estimated to range from 1° to 5° while transiting verticals in streams with mean flow velocities of 3.3 and 6.5 ft/sec at transit rates of 0.3 or 0.4 times the mean velocities. The sampler tilts down as it moves

downward and up as it moves upward.

2. If the tilt angle is known the angle β between the axis of the inlet nozzle of the sampler and the velocity vector of the flow relative to the sampler can be determined. This vector is the vector sum of the local stream velocity u and the transit rate R_T. Once this angle is known the relative sampling rate R can be read from curves such as in Figure A.5a. The error in sample concentration can then be read from curves like those in Figure A.3 which give the error in terms of relative sampling rate and angle between the nozzle axis and the velocity vector.

The calculations based on data in Figures A.3 and A.5a, measured gravity moment for the US D-49 sampler and estimated hydrodynamic coefficients showed that the relative sampling rate for upward transit exceeded that for downward transit. The relative sampling rate which ranged from 0.92 to 1.09 for the four conditions considered increased with stream velocity and was insensitive to sampler transit rate. The estimated errors in concentration for these extremes in sampling rate ranged from -2% to +2%.

3. Field tests of samplers were made by the U.S. Geological Survey in the Colorado River with velocities as high as 8.2 ft/sec and depths up to 26 ft. Under these severe conditions the US P-46 and US P-46S samplers gave relative sampling rates while transiting the flow of 1.04 and 0.94 for downward and upward transit, respectively. The approximate calculations also indicated that sampling rates on downward transit exceed those for upward transit. The average errors

in concentration in the field tests were zero for upward transit and -1.3% for downward transit.

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